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Improving the scalability of MAC protocols in Wireless Mesh Networks

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As the candidate's supervisor, I have approved this thesis for submission.

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University of Cape Town

To God for His love, grace, mercy, kindness, goodness, and favour.

And to my lovely wife Linda, sons Brahan Junior Mthulisi and Kganya Mthulisi and daughters Loyiso Mthulisi and Shalom Nokukhanya Mthulisi

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Abstract

Wireless Mesh Networks (WMN) offer increased capacity compared to Mobile Ad Hoc Networks (MANETS). They overcome the challenges of MANETS by combining a backhaul of static Mesh routers and mobile Mesh clients. WMN are auto configuring, self healing and self organising access networks. Different access networks can be integrated into a WMN forming a community last mile network.

WMN can operate as single hop and single channel networks. They can also be configured as multi hop and single channel networks. Furthermore, multi hop multi-channel and multi radio (M^3) options can be availed to increase the capacity of WMN. However, there is need to determine the optimal number of channels that can be supported by a single transceiver before the multi radio option is considered. An optimized single transceiver scheme will ensure that efficient systems are designed. Multi-channels should be, therefore, implemented at Medium Access Control (MAC) layer in a more efficient and scalable manner. Good coordination, selection, scheduling, and channel assignment algorithms should be implemented to improve the efficiency of multi-channels MAC protocols.

Multi-channel approaches come with new challenges that need to be solved to increase further the capacity of WMN. The new challenges are the terminal deafness problem, multi-channel Hidden Terminal Problem (HTP), network portioning and increased hardware costs. A multi-channel framework is required that minimizes the hardware cost of the system while ensuring that multi-channel interferences are reduced significantly. The framework should also facilitate network connectivity to ensure that there are no logical partitions in the network. The framework should be designed with a view of a more scalable network system.

Efficient utilization of multi-channels is critical for the success of multi-channel MAC protocols. The available bandwidth should be utilized efficiently to increase the end to end throughput. Unfortunately, current multi-channel MAC protocols are not efficient in the utilization of the multiple channels. Bandwidth is wasted through high signalling overhead. The poor utilization of the available channels is also affected by the following: channel coordination, channel selection, and channel scheduling strategies, which do not lend themselves to scalability and the efficient use of the multiple channels. Good channel coordination and selection techniques are therefore required to improve the efficiency of the multi-channel MAC protocols. These techniques should be coupled with effective and scalable signalling techniques, which reduce substantial signalling overhead.

A multi-channel Cyclical Scheduling Algorithm (CSA) is proposed to address these challenges. The CSA consists of the following components: the multi-channel switching technique, the data channel reservation and access technique, the inter-cycle technique, the Control Channel Inter Frame Space (CIFS), the network support infrastructure, a virtual orthogonal channel assignment algorithm, and the cyclical scheduling algorithm. These components are integrated to form the CSA scheme. A modular approach was employed in evaluating the components of the CSA.

The multi-channel switching technique ensures that all the terminals switch to the control channel immediately after transmitting data and Acknowledgement (ACK) packets on the data channels. They also switch to the data channels soon after successfully exchanging control packets. The switching penalty has been decoupled with the control channel and coupled with the data channels. The approach improves the efficiency of the control channel, which in turn improves the overall performance of the network. The scheduling capability of the control channel improves to ensure that it effectively drives more data channels. The main objective of the thesis is to achieve better scalability of WMN.

The data channel reservation and access scheme limits channel contention to the control channel. The data channels are reserved before they become available. The scheme reduces both the sensing and the channel switching durations. Limiting contention to control channel channels therefore, saves a substantial amount of bandwidth. The reservation of data channels is driven by a network infrastructure which assists terminals with insufficient network knowledge. The network support infrastructure keeps an up-to-date network status and records all the activities of the network in a distributed manner.

The inter-cycle technique allows data channels to be reserved when they are about to finish their current transmissions. This reduces the amount of time the control channel lies idle and it also limits the multi-channel switching cost (MSC) to the first cycle. The MSC is the wasted bandwidth in each data channel as it waits for its turn to transmission data. The control channel schedules data transmission to one data channel at a time while the rest of the data channels are idle thus wasting bandwidth. When the inter-cycle is not implemented the MSC will recur at every cycle.

The CSA framework also specifies an Inter frame space (IFS) called the CIFS. The CIFS replaces the Extended IFS (EIFS) implemented in a single channel environment in dealing with garbled packets and HTPs. In multi-channel environments, the EIFS is not appropriate and it degrades the performance of the network. The CIFS is set to the transmission duration of the CTS packet, if the garbled packet is the RTS otherwise, terminals defer for Short IFS (SIFS) duration.

The CSA scheme reduces the signalling overhead, improves the utilization of channels, reduces the effects of the MSC, and improves the efficiency of the control channel, overcomes the processing and storage constraints of mobile nodes.

The numerical results show a performance benefit of the CSA. The scheme is scalable and reduces the control signalling cost. It also limits the effects of the MSC to the first cycle. The thesis also proves that good scheduling techniques do improve the capacity of the network by availing more orthogonal channels at use.

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Glossary

Ad Hoc – Infrastructure-less WLAN

AIFS – Arbitration Inter Frame Space

AMCP – Asynchronous Multichannel Coordination Protocol

AODV – Ad hoc On-Demand Distance Vector

CBR – constant bit rate

CCA – Clear Channel Assessment

CIFS – Control channel Inter Frame Space

Control Channel – Is a dedicated channel set aside for signalling purposes

Control handshake – Used in this thesis to refer the exchange of RTS and CTS packets by the transmitter and receiver.

CR – Communication range

CSA – Cyclic Scheduling Algorithm

CSMA/CA – Carrier Sense Multiple Access with Collision Avoidance

CSR – Communication Sensing Range

CSZ – Communication Sensing Zone

CTS – Clear To Send

DCF – Distributed Coordination Function

DIFS – DCF Inter Frame Space

DSDV – Destination-Sequenced Distance Vector

DSR – Dynamic Source Routing

Dumb Agent routing – it is an ad hoc, one hop routing algorithm.

Dynamic routing – The route between the source and the destination is changed dynamically by the routing algorithm during the course of transmission, as a result a number of routes can be used to route packets.

EIFS – Extended Inter Frame Space

ETP – Exposed Terminal Problem

HTP – Hidden Terminal problem

IFS – Inter Frame Space

IR – Interference Range

LAN – Local Area Network

LIFS – Long Inter Frame Space

MAC – Medium Access Control

MANET – Mobile Ad hoc NETWORK

MRP – Missing Receiver Problem

MSC – Multi-channel Scheduling Cost

Multi-Channel – The use of a number of channels in the IEEE 802.11a, IEEE 802.11b and IEEE 802.11g standards

Multi-radio – The use of terminals equipped with at least two radios.

Multi-transceiver- use of a single radio which is equipped with a number of transceivers

Multi-channel single-transceiver MAC- employs many channels and a single radio with a single transceiver

Multi-channel multi-transceiver MAC- employs many channels and a single radio with many transceivers

NAV –Network Allocation Vector

NGN – Next Generation Networks

NGWN – Next Generation Wireless Networks

NOAH – NO Ad Hoc routing

Node – It is a mobile device capable of sending and receiving radio signals

Node Deafness – is synonymous with Missing Receiver Problem

PAN – Personal Area Network

PCF – Point Coordination Function

PHY – Physical layer

PIFS – PCF Inter Frame Space

PLCP – Physical Layer Convergence Protocol

QoS – Quality of Service

RIFS – Reduced Inter Frame Space

RTS – Request To Send

Scalability – a measure of the protocol's ability to process graceful increasing process loads

SIFS – Short Inter Frame Space

Static routing – The set route between the source and the destination is fixed.

Switching – When a terminal switches its radio from one channel to the next channel

TCP – Transmission Control Protocol

Throughput – is the average rate of packets which are received by a node through a communication link.

Terminal – Is synonymous with a node

Wi-Fi – Wireless Fidelity. It is a Wireless Local Area Network technology

WiMAX – Worldwide Interoperability for Microwave Access

WLAN – Wireless Local Area Network

WMN – Wireless Mesh Network

WPAN – Wireless Personal Area Network

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Chapter 1 Multi-channel MAC Protocols

1.0 Introduction

Multi-channel Medium Access Control (MAC) protocols offering high capacity are set to improve the quality of service (QoS) provisioning of wireless access networks. However, there are a number of challenges that have to be addressed to achieve the envisioned QoS. Existing Multi-channel MAC protocols under-utilize the capacity of data channels and suffer from high signalling overhead cost. These multi-channel MAC protocols have also created a new scheduling related problem referred to in this project as the Multi-channel scheduling cost (MSC). The MSC is the inability of multi-channel MAC protocols to schedule data transmissions to all the available data channels simultaneously. As data transmissions are scheduled, some data channels are placed in a queue for a long duration before they are serviced thereby under-utilizing the capacity of the data channels. Furthermore, the capacity of the control channel and its capability to schedule more transmissions are degraded by high signalling overhead costs.

Network connectivity is also a multi-channel MAC challenge. An ideal multi-channel MAC scheme should facilitate network connectivity. The scheme should also implement good channel selection and coordination techniques, which improve network connectivity. Multi-radio and multi-channel systems were proposed to solve the connectivity problem and other multi-channel MAC challenges. However, multi radio techniques are expensive, complex and suffer from signal linkages. Furthermore, the radio, which assigned to data channels, is underutilized during the channel assignment phase.

The multi radio techniques are also subjected to the effects of the MSC. The common dedicated control channel approach ensures total network connectivity. The approach is inexpensive and effective. It allows nodes to synchronize on the control channel and exchange network related status information. Unfortunately, the implementation of the common control channel is perceived to be causing a system bottleneck. A channel is said to have caused a bottleneck when it cannot provide sufficient bandwidth for the next transmission, while the other channels have enough bandwidth. We evaluate and analyze the effectiveness of the control channel approach in light of the perceived system bottlenecks challenges.

The control channel approach facilitates network connectivity and provides a common platform upon which terminals can listen on when idle. Terminals can also contend for the data channels through the control channel. Terminals within the communication range of either the sender or receiver can overhear sent control. The control channel approach also simplifies channel coordination and reduces a number of wireless interference challenges. Unfortunately, the perceived system bottleneck caused by the control channel has made this approach less attractive. The approach has been considered unfavourable. However, optimization techniques trading off the saturation challenge with connectivity may be the best

approaches that can solve the multi-channel coordination challenges. There is a need to study the saturation challenge extensively. The saturation problem is caused by the failure of a channel to meet the bandwidth requirements of the next transmission due to insufficient capacity.

The research interest in Wireless Mesh Networks (WMN) and multi-channels is motivated by the need for higher data rates, good QoS, and access ubiquity to wireless services. The consideration of WMN was necessitated by the unsatisfactory results achieved in Mobile Ad Hoc Networks (MANETS). The MANETS implemented the Institute of Electrical and Electronic Engineers 802.11 Medium Access Control (IEEE 802.11 MAC), which was enhanced over the past years; unfortunately no encouraging results were achieved. The attention soon shifted on to the WMN and multi-channels. WMN consists of a backbone of static mesh routers and mobile mesh clients as shown in Fig 1.1. The mesh client network is typically the MANET which is connected to a network of powerful mesh routers. The mesh client network connects to the Internet through the mesh backbone. The WMN architecture is designed to solve the shortcomings of MANETS.



Figure 1. 1 The architecture of wireless mesh network [1]

The family of IEEE 802.11 standard has been proposed as the specification for the MAC and the physical layers for WMN. The IEEE 802.11 MAC protocol implements the CSMA/CA, which was designed for single channel, single hop protocols. The physical layer, on the other hand has a provision for the use of multi-channels. The MAC protocols should therefore be redesigned and reconfigured to make use of the available multi-channels to improve the capacity of the WMN.

The implementation of multi channels however, results in the under utilization of the capacity of the channels. Furthermore, a new multi channel scheduling challenge has been identified. The scheduling challenge is referred to as the Multi-channel Scheduling Cost (MSC) in this

work. To the best of our knowledge this challenge has not been reported elsewhere. The MSC is caused by the inability of the control channel and scheduling algorithms to schedule concurrent transmissions to all the available channels simultaneously.

Over the years, MAC protocols have evolved from single radio single channel and single-hop MAC protocols to multi-channel multi-hop multi-radio MAC protocols. Multiple transceiver radios have also been considered instead of multi-radio techniques. All these attempts are endeavours to reconfigure existing single MAC protocols to work with multi channels in multi hop networks such as WMN. However, there are still open research issues, which require further attention.

Initially, researchers sought to enhance the existing single MAC protocols to achieve higher capacity. Some of the enhancement saw the implementation of the Request To Send/Clear To Send (RTS/CTS) and the Extended Inter Frame Space (EIFS). Unfortunately, these efforts did not yield good results. The failure to achieve the envisioned capacity through the enhancements of the IEEE 802.11 in single channel networks motivated MAC researchers to consider multi-channel MAC protocols. Current research seeks to develop efficient and effective coordination, channel selection, channel scheduling and efficient channel assignment techniques, which are ideal for multi-channel mesh networks. This thesis seeks to address these challenges and contribute to the design of effective and efficient multi-channel MAC protocols. Thus, the essence of this project is to design efficient, scalable and high capacity WMN MAC protocols.

The efficient coordination of multi-channels MAC protocols with a view of improving their efficiency and capacity while maintaining total network connectivity is the main research challenge in the design of scalable multi channel MAC protocols. Concurrent data transmissions take place on different data channels and it is assumed that these transmissions do not interfere with each other. The nodes should quickly synchronise to reduce the effects of missing receiver problems (MRP), the terminal deafness problem and the multi-channel hidden terminal problems, which degrade the capacity of multi-channel MAC protocols.

A single and common signalling channel technique, in principle, addresses all these concerns and issues. The common signalling channel is also known as the common channel where all nodes listen on when they are idle. Nodes also reserve the available data channels through the control channel. The implementation of a control channel raises a few design questions that have to be addressed. For example, what are the design requirements of such a multi-channel MAC? How much capacity should be allocated to the control channel to improve its scheduling capacity and to prevent it from causing system bottlenecks? What is the impact of the signalling overhead on the capacity and the performance of the control channel and the network? These and other issues are addressed in this project.

The project considers a single common control channel approach equipped with a single radio. Multi radio techniques were not considered due to the cost of hardware, signal linkages, complexity and the feasibility of equipping a small device with multiple radios. With multiple radios, design ingenuity and efficiency may be sacrificed for capacity, which

can be achieved by simply adding more radios. We therefore need to establish first the optimum or the maximum number of channels that can be serviced efficiently by a single radio before scaling up the number of multiple radios. The proposed algorithm assumes a multi-channel single radio MAC.

Multi transceiver MAC protocols can be viewed as a cost effective and less complex compromise of multi radio MAC protocols. Multi transceiver techniques make use of a single radio which is equipped with a number of transceivers while a multi radio system employs a number of radios on each device. However, we still have to deal with the problem of signal linkages and how we can use the available channels efficiently without just increasing the number of transceivers at the expense of efficiency. Given these challenges of multi radio techniques, the multi-channel MAC protocols (use of more than one channel to transmit data), which are equipped with a single radio, were considered as possible MAC protocols for the WMN in this project.

WMN are widely touted as the possible future community access networks offering high speed last mile broadband connectivity. They overcome the shortcomings of ad hoc networks by overlaying or integrating mobile terminals with static, high capacity and power efficient mesh routers. The static nodes have high processing power, energy efficient and act as a semblance of an infrastructure-based backbone of the mesh networks. However, more has to be done to position WMN as high speed last mile broadband wireless network solution for the next generation networks (NGNs).

One of the proposed directions of research aimed at increasing network capacity exploits the availability of the multi-channels at the physical layer by redesigning the MAC protocols to handle multiple channels. The results of these efforts are encouraging. Though encouraging, the implementation of multi-channels at the MAC layer has given rise to a new multi-channel MAC protocols challenge we refer to as the multi-channel scheduling cost (MSC). The MSC is caused by the poor utilization of control and data channels during the data transmission and channel assignment phases. The scheduling of channels is done sequentially; as such their capacity is under-utilized while they wait in the queue.

This thesis first presents, in detail a proposed cyclical scheduling algorithm (CSA) through which the multi-channel interferences such as the MRP can be addressed. The CSA is the multi-channel coordination, scheduling and channel selection scheme, which transmits data in phases. The CSA is designed to address the MSC, improve channel utilization and to reduce the idle durations of the channels.

1.1 The common control channel approach

The control channel is the driver of multi-channel MAC protocols, which implement a dedicated control channel. The control channel can either improve or degrade the performance of the protocol depending on its design. If the control channel has limited capacity or is poorly designed it may cause a system bottleneck. On the hand, if it is well designed and has enough capacity it can improve the performance of the network. The amount of signalling on the control channel should be reduced to improve the capacity of the

control channel. Furthermore, good channel scheduling and assignment techniques should be employed to address the effects of the MSC. We review the effectiveness of the MAC protocols in Section 1.3 in reducing the signalling overhead. It is envisaged that the reduction of the signalling overhead coupled with an efficient MSC solution will improve the performance of the MAC protocols implementing a dedicated control channel.

1.2 Need for scalable MAC protocols

The need for high data rates has necessitated research on the MAC protocols. The MAC protocols suffer from a lot of interference and significant bandwidth is lost. A solution which addresses these challenges increases the scalability of MAC protocols. The MAC protocols should also be optimized for real time and time bounded data in access networks. In the next generation networks, a number of network technologies will be integrated and different data streams will traverse and move across different platforms before arriving at their destinations. It is paramount that the access networks such as the WMN be optimized for quality of service in a converged communication environment. The scalability of MAC protocols will ensure the provisioning of quality of service, reach, and desired capacity is achieved. Scalability is a measure of a protocol's ability to process graceful increasing process loads as the size of the network increases or when the volume of traffic increases.

1.3 Existing Multi-Channel MAC Protocols

Some of the few schemes that employ either a temporary or a dedicated common channel were proposed in [2], [3] and [4]. In [2] a temporary signalling channel called a default channel is implemented only during the Announcement Traffic Indication Message (ATIM) window. In the data window the scheme is used for data transmission. The signalling delay is reduced through the implementation of a data structure called the Preferable Channel List (PCL). The PCL is employed in data channel reservation.

Nodes exchange the ATIM/ATIM-RES/ATIM-ACK during the ATIM window and then the RTS/CTS packets during the data window. The signalling duration is long and its overhead cost is too high. All the signalling packets have been increased in size. A data channel is selected by a number of transmitter-receiver pairs during the ATIM window. The pairs then contend for these data channels during the data window increasing the signalling cost. The probability of collisions is high. One pair can reserve only one data channel during a beacon interval.

The signalling duration is too long; as a result the severe effect of the MSC is experienced. The utilization of the channels is very poor. The signalling delays should be reduced to address the effects of the MSC.

In [4] a notion of a control and data window is exploited. A temporary common signalling channel is implemented during the control window. The signalling channel is called the default channel during the control window and is then referred to as a data channel during the data window. One data channel is selected by a number of transmitter-receiver pairs and the signalling packets have been increased in size. There is also an additional signalling packet called the reserve (RES) packet. Piggy backed channel information on control channel is used to reserve the data channels. The protocol is similar to [2]. The bandwidth of the data

channels is wasted during the control window. The data channels are not utilized during the control window and this gives rise to the MSC.

The scheme proposed in [3] does not implement the control and data windows though the notion of preferable channel data structures was considered. Data channels are reserved through the local data structures. If a pair fails to reserve a data channel, they can contend for another chance to reserve a different data channel. Assuming that all pairs only succeed in reserving a data channel in their second attempts, this is a significant overhead cost and a worst case of the MSC. The sizes of the control packets were increased and a new control packet was also introduced, which further increases the signalling overhead. As a result, channels are underutilized and significant bandwidth is lost.

Furthermore, the scheme is not optimized to avail network information to joining and returning nodes in time for them to make quick decisions. They are rather required to defer until they have adequate network information. This is also a manifestation of the MSC and the poor utilization of the bandwidth of the channels. On the other hand terminals defer indefinitely their transmissions in a newly deployed network. In a new network all the nodes would be having insufficient information about the status of the network. The defer rules proposed in this work do not ensure that communication takes place in such a situation.

There is a need therefore for a scheme, which reduces the signalling overhead costs, improves the utilization of channels at the same time availing adequate network information to joining, and returning nodes. The scheme should be designed to facilitate communication in a new network and reduce delays incurred by nodes as they defer their transmissions for the purposes of first acquiring adequate network information.

The CTS packets reserve a data channel; unfortunately the nodes in the sender neighbourhood and outside the receiver's communication range do not overhear it. Mobile nodes have limited processing power and storage capability. They cannot process efficiently the local node tables and store the processed information.

The proposed CSA is a new multi-channel coordination and scheduling MAC framework which improves the capacity of the control channel and improves the performance of the overall network. As such, the CSA increases achievable throughput, reduces signalling overhead cost and improves the scalability of WMN.

1.4 Problems in Existing MAC protocols

A number of multi-channel MAC protocols have been developed. The main objective of the most MAC schemes is to improve network performance and increase achieved throughput. The schemes can be divided into three broad categories, which can be further classified into specific categories. In the first category, there are MAC protocols, which employ a single transceiver and a common control channel. These protocols make use of existing and new control packets in conjunction with data structures to reserve data channels. The sizes of the existing control packets have been increased. The control handshake incurs high overhead

costs. The data channels are underutilized during data channel negotiation phase and their bandwidth is wasted.

The second category consists of multi-channel MAC protocols, which implement at least two transceivers. They are referred to as the multi-channel multi-radio MAC protocols in this project. The shortcomings of these protocols are their complexity and high hardware costs. The second transceiver and the data channels are underutilized during the data channel negotiation phase. The protocols also partition the network logically.

Lastly, there are channel hopping multi-channel MAC protocols, which establish and maintain a hopping sequence. Nodes have to maintain their own independent hopping sequences, which results in lack of network connectivity. The protocols also require synchronization. The hopping sequences are advertised through broadcast packets, which results in broadcast storms. The broadcast packets also fail to reach some nodes, which are either hidden or deaf. The uniqueness in node hopping sequences makes it very difficult for the broadcast packets to be delivered to all the nodes.

In the sequel we discuss some of the multi-channel MAC protocols under these categories. A few examples are chosen to put into perspective the shortcomings of these protocols, which are highlighted above.

1.4.1 Single transceiver multi-channel MAC protocols

The examples of single transceiver multi-channel MAC protocols are: the dedicated control channel MAC protocols [5], the busy tone control channel MAC protocols [6] and window based MAC protocols, which implement a temporary control channel [4]. All the protocols underutilize the data channels during the data channels negotiation phase. They also degrade the capacity of the control channel. For example, the busy tone protocols send busy tones on the dedicated control channel. The window based and dedicated control protocol MAC protocols have introduced new control packets and increased the sizes of the current control packets. As a result, the control channel is degraded by high signalling overhead costs.

In [5], both the sender and receiver have to sense all the channels before reserving a data channel. The nodes incur both sensing and channel switching costs, which degrade significantly the capacity of the control channel. They also increase the severity of the MSC. For example, if there are eleven data channels each of the eleven channels have to be sensed twice and the sender and the receiver should also switch to all the eleven channels. The sensing and channel switching times amount to a very high cost, which degrades significantly the capacity of multi-channel MAC protocols.

The busy tone MAC protocols [4] assume that a node can send data on two data channels simultaneously. Unfortunately, this is not possible. A node has to switch between channels to send on one channel at a time.

A multi-channel MAC model employing a single transceiver has not been developed to analyze the impact of the signalling overhead cost on the control channel and to analyze the

effects of the multi-channel scheduling cost. To the best of our knowledge, a multi-channel scheme, which reduces the signalling delay and solves the MSC, has not been designed.

1.4.2 Multi-transceiver multi-channel MAC protocols

The multi-transceiver multi-channel MAC protocols can be categorized into contention based [7] [8] and user based categories [9] [10]. In the contention based MAC protocols, the nodes have to reserve the data channels and release them after use, while in user based category nodes select a fixed data channel and retain it. The contention based protocols incur higher channel switching costs than the user based MAC protocols. The user based MAC protocols do not have to switch onto the data channel but the contention based have to. Unfortunately both classes under-utilize the data channels during the negotiation phase. The protocols are also complex and expensive in terms of the hardware costs.

The multi-transceiver multi-channel MAC protocols have also introduced a number of control packets and increased the sizes of the existing control packets. The number of the control packets and their sizes degrade the performance and capacity of the control channel and increase the effects of the MSC. The channels lie idle for longer durations. In [10] network connectivity is a challenge as the nodes are allowed to listen on different channels. The network is therefore segmented logically into several logical partitions, which make communication and broadcasting of packets impossible.

The model to analyze the effect of the signalling overhead cost on the control channel and the effects of the multi-channel scheduling cost has not been developed. Better strategies of improving the efficiency and the utilization of the bandwidth of the data channels are yet to be designed.

1.4.3 Channel hopping multi-channel MAC protocols

The channel hopping protocols [11] do not employ the concept of the control channel. They follow a hopping sequence and each node establishes its own hopping sequence. The difference in hopping sequences partitions a network into logical segments. The protocols also require time synchronisation, which is a challenge in mobile networks. Nodes have to switch onto all the available channels and in the process incur high overhead costs. The need to switch frequently increases the effects of the MSC.

The channel hopping protocols promote the idea of packet buffering. Buffered packets are subjected to transmission delays, which degrade the quality of service of delay bounded packets. They also require high system service rates for better management of the buffers and the queues.

The channel hopping protocols are not designed and optimized for the delivery of broadcasted packets. The delivery of broadcast packets is not possible and may cause the network to be unstable.

All the multi-channel MAC protocols assume that the available channels are orthogonal. It is envisioned that channels are assigned and used in an orthogonal manner. The most possible way is to increase the frequency band and reduce the number of available channels. On the

other hand, orthogonal aware channel selection techniques can ensure that channels are orthogonal at use. A model which ensures that the channels are non-overlapping at use while their number is not significantly reduced is preferred. We propose and develop a channel selection and scheduling model, which provides enough separation of channels and provides more orthogonal channels at use.

Multi-channel MAC protocols make use of the EIFS, which was designed for single channel MAC protocols. They also assume that timeouts should be set to expire at the end of data transmission, which is typical of the single channel MAC protocols. The EIFS and the timeouts have to be reconfigured and adjusted to suit the functionality of multi-channel MAC protocols. In multi-channel MAC protocols, concurrent data transmissions are possible, hence the need to reconfigure the EIFS and the timeouts.

1.5 Hypothesis

We hypothesize that reducing the signalling overhead cost of the control channel and the multi-channel scheduling cost can improve the scalability and the capacity of the Wireless Mesh Networks. Furthermore, intelligent coordination, channel selection and assignment algorithms will enhance the performance of the multi-channel MAC protocols; and to ensure that channels are selected and assigned in an orthogonal way. The performance of the network can be further improved by ensuring that terminals with insufficient knowledge of the network acquire up-to-date network status from the network support systems to expedient the transmission of data.

1.6 Research Questions

The thesis answers the following research questions:

1. Does the implementation of a dedicated control channel create a system bottleneck?
2. Can the overall network performance be improved by reducing the signalling overhead cost on the common channel?
3. How does the multi channel scheduling cost degrade capacity?
4. What is the performance benefit of solving the multi channel scheduling cost?
5. To what extent does the channel switching time degrade the performance of multi channel MAC protocols?
6. What is the effect of channel under utilization in multi channel MAC protocols and can this effect be addressed to improve the performance of the MAC protocols?
7. Is the Extended Inter Frame Space appropriate in multi channel MAC protocols?
8. Can channel assignment and scheduling algorithms be configured to ensure that overlapping channels are assigned in an orthogonal way to improve network capacity?

1.7 The research objectives

The scalability of multi-channel networks can be improved in twofold: by increasing the capacity of a common single signalling channel or by either eliminating or reducing the effects of the MSC. The capacity of the control channel can be improved by minimizing the scheduling delays and signalling overhead costs. The end-to-end delay and the idleness of the control channel should be reduced to increase the capacity of the control channel and the capacity of the network. The utilization of channels should be efficient and bandwidth wastage should be avoided.

The main objective of this project is to reduce the multi-channel scheduling cost and the control channel signalling overhead cost in order to increase the capacity of the control channel and the scalability of WMN. Furthermore, it is premised on the provision of a virtual orthogonal multi-channel MAC protocol.

These objectives are achieved by:

- Reducing the sensing duration
- Reducing the channel switching delays associated with channel sensing
- Redesigning the EIFS and introducing a new IFS called the CIFS
- Designing an inter-cycle duration, which ensures that data channels are reserved before their current data transmissions are completed. This reservation improves the capacity of the control channel and its scheduling capacity
- Reducing the Multi-channel Scheduling Cost (MSC) to improve network capacity and to reduce end to end delay.
- Reconfiguring the channel switching delay to improve the capacity of the control channel.
- Designing a virtual orthogonal channel selection and coordination MAC scheme

1.8 The scope of the research

The thesis focuses on the design of multi-channel MAC protocols for the WMN, which implement a dedicated control channel. It focuses on wireless local area networks in which WMN offers the best architecture. WMN improves and enhances the existing multi-channel MAC schemes. The capacity of the control channel has been identified as the main performance metric. The investigations are therefore centred on the signalling overhead of the control channel and on the utilization of both the control and data channels. Considerable bandwidth is wasted due to underutilization of both control and data channels. The project therefore reduces the effects of bandwidth wastage, the multi-channel scheduling cost and limits its effects to the initial phase of data communication. In the existing multi-channel MAC protocols, the effects of the MSC are recurring and repetitive. Lastly, the project presents and analyzes a virtual orthogonal channel scheduling technique. The virtual algorithms avails more orthogonal channel by assigning data channel in a non overlapping manner. It ensures that the selection and use of data channels is virtually orthogonal in use to increase the number of available data channels to achieve high end to end throughput.

The proposed CSA was not implemented in both real world and test bed environments due to cost implications. Furthermore, the HTP and ETP interference challenges were not investigated due to time constraints.

1.9 The contribution of the research

The thesis presents a critical analysis and a survey of multi-channel MAC protocols and shows their limitations. Techniques designed to address these challenges have been proposed and are effective. The multi-channel MAC protocols are classified according to how the control channel is implemented and used. The thesis also shows how high signalling overhead degrades the capacity of the common control channel, which affects the performance of the MAC protocols.

We show how channel coordination and selection techniques degrade the capacity of multi-channel MAC protocols. The channel coordination and selection techniques are presented as the multi-channel scheduling cost. It is a channel scheduling cost, which relates to the under utilization of data channels during the data channel reservation phases. The multi-channel scheduling cost was first identified in this project. The thesis shows that the multi-channel scheduling cost is recurring in existing multi-channel MAC protocols.

In this thesis, the multi-channel scheduling cost has been characterized and its effects reduced and limited to the first transmission cycle. The proposed solution model ensures that the challenge of the multi-channel scheduling cost does not recur and that its effects are minimized and restricted to the first cycle. As a result, the utilization of channels is improved. The novelty of the proposed cyclic scheduling algorithm is in its ability to address the MSC challenge.

A basic and simple model for analyzing the saturation problem of channels is presented. The model is designed to evaluate the capacities of channels and establish channels that are likely to saturate first causing a system bottleneck. The model incorporates the channel switching delay in the analysis.

The impact of the channel switching delay on network performance is put into perspective. It is shown how it degrades significantly the performance of multi-channel MAC protocols. The analysis was done in a simulated environment with different network sizes. The results show that the channel switching penalty has a major impact on the performance of the multi-channel MAC protocols. The impact of the switching time has not been investigated in different sizes of networks. We further propose a solution which lessens the impact of the switching time on network performance.

Markov chains and queuing network models are employed in analyzing the effect of the signalling overhead on the capacity and performance of the control channel. The control channel is presented as a service station connected to multi input service stations and to multi output service stations. The modelling tools show the significance of the control channel. The capacity of the control channel have to be improved for better performance, hence the emphasis on the reduction of control channel overhead costs. The Markov and queuing techniques are ideal in modelling queuing behaviour, arrival and service rates of network systems.

A model, which improves the capacity of the control channel, is proposed. The model reduces the signalling overhead, reconfigures the channel switching delay and also addresses the multi-channel scheduling cost. The model proposes a cyclic scheduling algorithm in which the coordination, selection of data channels and the scheduling of data transmissions is phased. The phases are synonymous with time slots, in which data channels are reserved. In a cycle with ten data channel, a cycle would consist of ten phases, one for each data channel.

The thesis also proposes a model for supporting and equipping joining nodes, returning nodes and nodes in a newly deployed network, which have inadequate network information to enable them to initiate communication. These nodes have limited knowledge of the state of

the network because they would not have been listening on the control channel. The nodes have to listen on the control channel and update their local data structures when they overhear control packets. However, joining and returning nodes would be less informed. In the case of a new network, all the nodes would be waiting to overhear control packets before initiating any communication. The model employs a network support infrastructure of mesh routers, which keep track and record the list of busy and idle data channels and transmission durations of the data packets including remaining transmission durations. This information is availed to nodes with inadequate knowledge to facilitate their communication. The implementation of the network support system ensures that nodes do not defer their next transmissions. Chapter three discuss protocols, which allow nodes to defer their transmissions until they have acquired adequate knowledge of the network.

The EIFS has been configured and replaced with two proposed inter frames space; one for the single channel and the other for multiple channel MAC protocols. The EIFS is designed to protect ACK packets from Hidden terminals. Furthermore, nodes defer for EIFS during once they receive erroneous control packets. In a multi-channel environment, there is no need to protect ACK packets since they are transmitted on a different channel. In addition, there is no need for the deferment after a node had received an erroneous packet. A node can use the next available data channel. In the single channel environment, it has been replaced with the IFS called the Long Inter Frame Space (LIFS), while in the multiple channel MAC protocol; it was replaced with the IFS called the Control IFS (CIFS). The LIFS is designed to inhibit hidden terminals in the receiver's communication zone while the CIFS was necessitated by the need to improve the scheduling capacity of the control channel and to address the multi-channel scheduling cost, which was first identified in this project.

Lastly, a virtual orthogonal data channel assignment algorithm is proposed, implemented and evaluated. The algorithm seeks to increase the number of data channels by ensuring that the selection and the use of non orthogonal channels is in fact orthogonal in use. It implements simple concepts of selecting data channels sequentially and ensuring that the next data channel to be selected is orthogonal to the previously selected data channel. The channels will be overlapping in the physical sense however, an orthogonal channel assignment criteria is implemented to ensure that these data channels are non-overlapping in use. The data channels will be selected and assigned to communicating by pair in an orthogonal way. The virtual orthogonal algorithm ensures the desired channel separation as data channels are assigned to nodes.

The above mentioned contributions are contained in the following publication list by this author.

Peer-Reviewed Conference Publications

1. **Mthulisi Velempini** and Mqhele E. Dlodlo. Combating the effects of Hidden Terminals in Multi Channel MAC Protocols (SATNAC 2008) - Wild Cost, South Africa, 7 – 10 September 2008, ISBN – 978-0-620-41696-2

The paper shows how the CSA platform addresses the Hidden Terminal problem and reduces its effect. It shows that the control channel can be effectively used to solve multi-channel interference challenges. However, in the case of a Hidden terminal problem, nodes receiving erroneous packets can reserve the control channel successfully without interfering with other nodes. The interference manifests on the data channels. The delayed manifestation of the hidden terminal problem is solved by scheduling transmission in timeslots with the access to data channels ordered in a sequential manner in this paper.

2. **Mthulisi Velempini** and Mqhele E. Dlodlo. Analyzing the effects of increasing data channels and the number of data flows on network performance (Wireless VITAE 2009) – Denmark, 17 – 20 May 2009, ISBN 978-1-4244-4067-2

The paper investigates whether the size of the network and the number of data channels have an effect on the network performance. Different network sizes and networks with different number of data channels were considered. The paper shows that the size of the network does not degrade performance. Furthermore, the increase in the number of data channels does not improve performance. It increase aggregated system capacity.

3. **Mthulisi Velempini** and Mqhele E. Dlodlo. A multiple channel selection and coordination MAC Scheme (Mesh 2009) – Greece, 18 – 23 June 2009, ISBN: 978-0-7695-3667-5

The paper proves that multi-channel networks do not improve the performance of the network though their benefits are in improved aggregate capacity. As a result, data channels cause a system bottleneck. They saturate ahead of the control channel. The paper proved that the control channel does not cause a bottleneck and that its capacity can be improved to improve network performance. This work is based on the proposed CSA.

4. **Mthulisi Velempini** and Mqhele E. Dlodlo. Arresting the effects of Missing Receiver Problems in Multi-Channel Systems (BroadBandCom 2009) – Poland, 15 – 18 July 2009

This paper shows how the CSA reduces the effects of the missing terminal problem from 33.33% to 8.33%. In the CSA the effect of the missing terminal problem is limited to the transmission duration of the control packets instead of the capacity of the control channel. The paper also models all the components of the proposed CSA scheme.

5. **Mthulisi Velempini** and Mqhele E. Dlodlo. Understanding Channel Saturation in Multi-channel MAC Systems (SATNAC 2009)–Swaziland, 30 August – 2 September 2009, ISBN: 978-0-620-44107-0

The paper studies and examines the saturation problem in generic multi-channel MAC protocols. The paper considers a common channel approach using channel occupancy and the length of transmitted packets. It improves that the control channel approach does not cause bottlenecks. The paper argues for the implementation of the control channel as it facilitates total network connectivity.

6. **Mthulisi Velempini** and Mqhele E. Dlodlo. The analysis and the evaluation of the performance of the channel switching penalty constrained Multi-channel networks (AFRICON 2009) – Kenya, 23 – 25 September 2009, ISBN: 978-1-4244-3919-5

The paper investigates the effectiveness of the proposed CSA in improving network performance. The paper uses the packet drop rate and dropped packets metrics to evaluate the scheme. The results show that the proposed scheme does improve network performance. They also show that the scheme is scalable.

7. **Mthulisi Velempini** and Mqhele E. Dlodlo. Analyzing the effects of the RTS based data channel reservations and access scheme in Multi-Channel Systems with enhanced channel switching technique (ADHOCNETS 2009) – Niagara Falls, Canada, 23 – 25 September 2009, ISBN: 978-963-9799-66-0

The paper shows that there is performance benefit for limiting channel switching time and carrier sensing to the control channel. The paper considered a scenario in which data channels are available at the transmitter end.

8. **Mthulisi Velempini** and Mqhele E. Dlodlo. Improving the Performance of Multi-channel Systems by Limiting Contention to the Control Channel (ICN 2010) – Menuires, France, 11-16 April 2010, ISBN: 978-0-7695-3979-9

The carrier sensing scheme was extended to the receiving node. The performance also increased significantly. The results showed that when data channels are free or available both at the transmitter and receiver ends, network performance would be improved.

9. **Mthulisi Velempini** and Mqhele E. Dlodlo. Evaluating the impact of the signalling delay on the control channel (MELECON 2010) – Valletta, Malta, 26 – 28 April 2010, ISBN 978-1-4244-5794-6

The paper evaluates the impact of the switching time on network performance. It also models the multi-channel MAC protocols using Markov and queuing networks. It shows that the proposed scheme reduces the effects of the channel switching time and the control channel overhead cost.

10. **Mthulisi Velempini** and Mqhele E. Dlodlo. The implementation of LIFS in a single channel MAC protocol (MELECON 2010) –Valletta, Malta, 26 – 28 April 2010, ISBN 978-1-4244-5794-6

The paper implements a longer IFS scheme in single channel MAC protocols to combat the effects of the hidden terminal problem in the receiver neighbourhood. The end to end delay shows that the scheme is very effective. On the other hand, the throughput results show that the scheme improves fairness. The implementation of the Longer IFS has been extended to the proposed CSA in this thesis. However, it had to be reconfigured to work in the multi-channel environment.

Journal Publications

1. **Mthulisi Velempini** and Mqhele E. Dlodlo. The design and implementation of the Cyclic Scheduling Algorithm: A multi-channel MAC protocol – Published by the Journal On Advances in Internet Technology, volume 3, numbers 1 and 2, 2010, article inttech_v3_n12_2010_3, Pages: 29 to 42 ISSN: 1942-2652

Book Chapters

1. **Mthulisi Velempini** and Mqhele E. Dlodlo. An RTS Based Data Channel Reservations and Access Scheme in Multi-Channel Systems. Book title: Ad Hoc Networks, Springer Berlin Heidelberg, ISSN: 1867-8211(Print) 1867- 822X (Online) – ISBN – 978-3-642-11720-0 (Print) 978-3-642-11723-7 (Online)

1.10 Thesis Outline

Chapter two overviews the background information on ad hoc networks and wireless mesh networks and how these technologies impact on the research questions under study. It chronicles the search for high data rates, which saw research moving from ad hoc networks to wireless mesh networks; single channel MAC protocols to multiple channel MAC protocols. The chapter reviews briefly the multi radio and multi transceiver techniques, which have been proposed as possible solutions to the quest for high data rates. The chapter also reviews the challenges of multi channel MAC protocols and the need for scalable and cost effective MAC protocols. The emphasis is on the efficient utilization of channels and the reduction of signalling overhead and multi-channel scheduling costs.

Chapter three reviews multi-channel MAC protocols and categorize them into five distinct taxonomies. The chapter focuses mainly on multi-channel MAC protocols, which implement a notion of a common signalling channel. The five categories of multi channel MAC protocols are evaluated in terms of their efficiency in utilizing data channels and in reducing both the multi-channel scheduling cost and the signalling overhead. The design considerations for multi-channel MAC protocols, which increase the capacity of the control channel are presented and discussed. The main objective of our proposed model is to increase the capacity of the control channel. The control channel approach is preferred for network

connectivity. It is also easy to coordinate multiple channels through a common reference point.

Chapter four proposes a Cyclic Scheduling Algorithm (CSA), which is designed to schedule data transmission in phases. The chapter presents and discusses all the components of CSA scheme and their functionality. The proposed architecture of the wireless mesh network is also presented and discussed. The proposed architecture is designed for the implementation of a network support backbone infrastructure of the CSA scheme. Analytical diagrams, which represent the proposed scheme, are also presented. The diagrams explain the functionality of the proposed scheme.

Chapter five discusses a number of analytical models, which are designed to show the significance of the proposed CSA scheme. The models seek to show how the scheme is likely to achieve better results. The models validate the proposed scheme and show how it addresses the issues raised in this thesis. The chapter investigates whether the CSA is likely to be affected by system bottlenecks and, which channel or channels are likely to saturate ahead of others. The chapter also presents a Markov and queuing models, which show how the proposed scheme improves the capacity of the control channel and its scheduling capacity. The control channel is presented as a single service station connected to multiple input service stations and to multiple output service stations.

The effects of the channel switching times are characterized and analyzed through network simulations. The effects of the channel switching times are analyzed in the context of different network sizes to ascertain its effects in different networks.

In chapter six, the simulation model is presented. The chapter discusses the simulation scenarios and the network configurations. The simulations parameters are also detailed including the simulation scenarios. The results of the different simulation scenarios are presented and discussed. The results are compared to similar multi-channel MAC protocols, which employ the idea of a control channel. In the interpretation and discussion of the results, it is shown how the results of the scheme address some of the research issues discussed in this thesis. The performance of the proposed scheme is therefore discussed and evaluated in this chapter. Its limitations are also highlighted.

Chapter seven presents the virtual orthogonal MAC algorithm. The model is presented and evaluated. The chapter briefly evaluates the effectiveness of the proposed channel assignment model and highlights the significance for good channel assignment strategies.

In chapter eight, the thesis is concluded with proposed future research directions, future work and recommendations. The chapter summarises the thesis and gives the overview on whether the research objectives were met. The successes and shortcomings of the thesis are also highlighted.

Chapter 2 Overview of Wireless Technologies

2.0 Introduction

This chapter shows how the advancement of mobile wireless technology led to the birth of WMN. It also shows why there is a need for scalable MAC protocols. WMN is designed to offer universal access in response to the anywhere, anytime, with anyone and through any network paradigm. WMN seeks to provide wireless broadband access to end users at a reasonable cost. It is composed of a backhaul of static or less mobile Mesh Routers (MR) which has replaced the need for Access Points (AP) and the need to connect APs individually to the wired backbone using expensive cables. Running separate cables for each AP is an expensive approach which is not scalable. The expensive cables and inflexible APs have been replaced with a scalable set of “hot zones” of mesh routers.

The backhaul is the access wireless system which enables downstream communication systems to connect to the Internet backbone. Mesh routers offer robust, self-healing, auto-configuring and self-organizing gateway functionality to the Internet backbone. The backhaul provides a last mile access to ad hoc and less mobile Mesh Clients (MC) which are also known as the Independent Basic Set Structure (IBSS). This setup gives birth to a heterogeneous network of MC and MR. Unfortunately; most MAC protocols do not consider the fact that the characteristics of the MRs are different from the MCs. The performance of MAC protocols is critical to overall performance of the network. Figure 2.1 depicts the components of WMN. It also shows different configurations of WMNs in which different wireless technologies are integrated in a mesh mode.

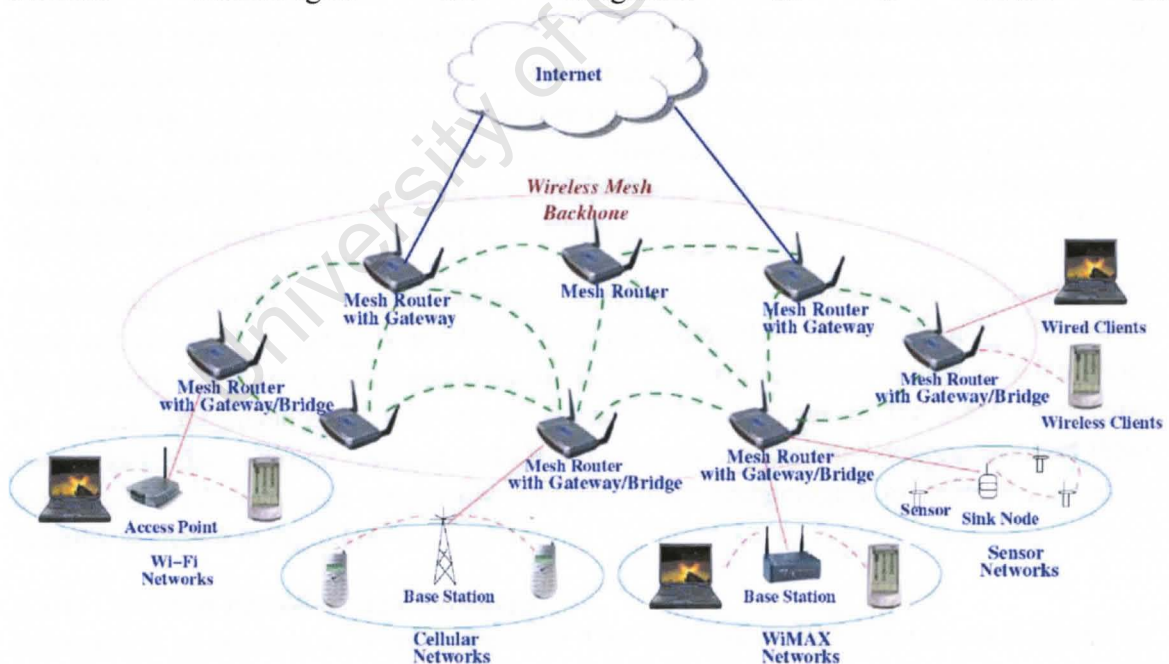


Figure 2. 1. The integration of WMN with other wireless technologies [1]

There is a need to redesign and optimize the MAC protocols given the vast improvements at the Physical (PHY) layers. There have been unprecedented advances at the PHY layer, which

are yet to be matched at the MAC layer. Smart antennas, Multiple-Input Multiple-Output (MIMO), directional antennas, multiple channel, multiple radios and multi-hop techniques have been introduced at PHY layer. However, the MAC layer is still single hop, single channel point-to-point communication.

In this chapter, we preview briefly all the major wireless technologies and attempt to show why Wi-Fi is the wireless technology of choice for this research. The chapter also discusses initiatives to integrate Wi-Fi with Bluetooth and WiMAX. In general background information of wireless technologies and subsequent advances leading to current research in WMN is highlighted.

2.1 Wireless Technologies

Wireless communications technologies gave birth to portable and mobile networks. Bluetooth, WLAN and Cellular are the earliest wireless communication technologies. The Bluetooth technology is limited in communication range and capacity. It is used for short distances and limits the mobility of devices. It provides communication ranges of up to a maximum of 50 metres. The WLAN technology does provide the much needed mobility and coverage. It offers broadband speeds with a maximum of coverage of 250 metres. It became a technology of choice at public and meeting places such as restaurants, colleges, airports, train and bus stations, conferences, hospitals and parks. The Wi-Fi technology can also be implemented by private companies and individuals for Internet access. It is cheap and cost effective.

The cellular technology gained more popularity over the WLAN technology when it was commercialised. It offers a true mobility experience to users and ubiquitous communication. Unfortunately, it is a voice-based communication system. It is not suitable for internet access and for the transfer of data in large volumes. However, with advancement of the cellular technology, new features were introduced. The evolution saw cellular technology transmitting short messages, emails and now short multimedia messages.

The cellular technology is capital intensive. It requires heavy investments in infrastructure such as base stations, switches and Radio Network Controllers. This technology also offers low capacity. The three technologies (Bluetooth, WLAN, and Cellular) though have a number of benefits and advantages; they do not meet the requirements of the Next Generation Networks (NGN). Current research seeks to improve the capacity and address some of these challenges. There are also attempts to integrate these technologies to achieve maximum benefits as shown in Fig 2.1.

2.1.1 Wireless Personal Area Networks

Bluetooth is an example of Wireless Personal Area Network (WPAN) and it was launched by Ericson in 1994. The technology began taking shape in 1998. The technology was designed for the exchange of data and voice data stream at a rate of 1 Mbps. An example of a WPAN is shown in Fig 2.2. At its launch it used the short range radios in the 2 GHz frequency band. The Bluetooth was limited in coverage and its transmission range was 5 metres. With the advancement of the Bluetooth technology, transmission ranges of 100 metres are now

possible. It now sits between the 2.4 and 2.4835 GHz frequency bands and offers theoretical transmission speeds of up to 3 Mbps.



Figure 2. 2. A Wireless Personal connecting home device through Bluetooth Technology [12]

The Bluetooth technology is an open wireless standard which provides seamless data exchange over short distances. The technology is very efficient in power consumption. It is described as a low energy protocol. Bluetooth has been integrated with IEEE 802.11 in the Alternate MAC/PHY version which offers high transmission speeds of up to 24 Mbps. However, these are theoretical data rates. Its integration with IEEE 802.11 positions Wi-Fi as a market leader and a wireless network of choice.

The Bluetooth technology has several disadvantages. It is suitable for non resident equipments and associated applications. It is also limited in capacity and offers limited mobility. It cannot be scaled up and be used for broadband wide area networks. Technologies that can replace Ethernet local area networks such as the WLAN are therefore required.

2.1.2 Mobile Wireless Technology

The cellular technology is the oldest mobile technology. It was commercialized in North America in 1983. The technology offers a number of advantages such as increased capacity and the widest communication range of up to 50 km in open areas. It consumes less power and reduces co-channel interference. Cellular technology supports mobility and ubiquitous communication. The main disadvantage of cellular technology is its limited capacity in comparison to Wi-Fi and Ethernet. It is best suited for voice communication.

The first commercial mobile telephone system known as the zero generation of the cellular technology (0G) was launched in 1971 in Finland. The first generation of cellular network was later launched in 1973. Major revolution in the cellular technology took place in 1990s with the introduction of 2G, 2.5G and 2.75G cellular networks. However, the capacity of these networks was still limited and higher data rates were sought. The introduction of the

third generation in 2001 offered better data rates, unfortunately not at the designed levels envisioned for fourth generation networks. In comparison to Cellular technology, the WLAN offers better data rates and is best suited for data applications, hence the emphasis on WLAN.

2.1.3 Wireless Local Area Network

The Wireless Local Area Network (WLAN) technology supports two types of networks, the infrastructure based (Figure 2.3) and the infrastructure-less (Ad hoc) (Figure 2.4). The infrastructure less mode does not rely on the services of a central device such as the access point or router. It allows nodes to communicate directly. Though the ad hoc mode is preferred for mobility, it is slower than the infrastructure based mode. It is susceptible to interference, hidden node and exposed node problems. As result of high interference, low data rates are achievable. There is therefore a great need to reduce this interference at the MAC layer. However, a lot of research work has been done in attempt to reduce interference and increase the capacity of the ad hoc mode. Unfortunately, no significant results have been achieved. This realisation has prompted researchers to consider other alternatives and other access networks such as the WMNs.

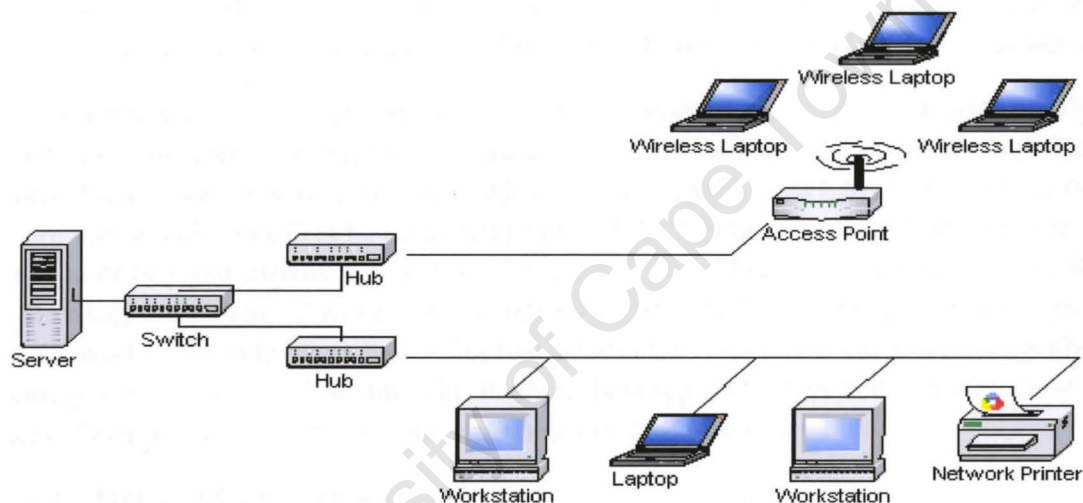


Figure 2. 3. An Infrastructure based Wireless Local Area Network [13]

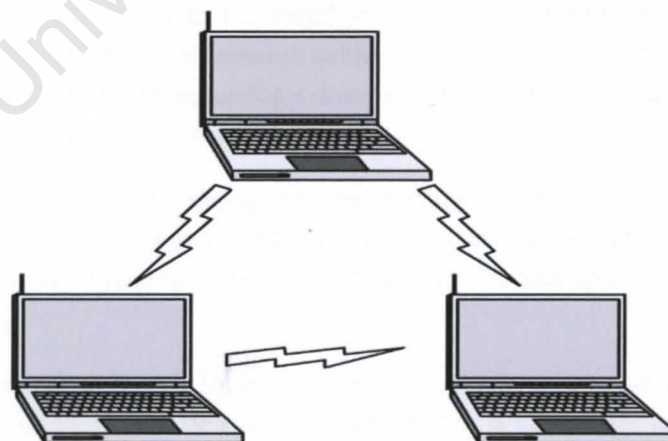


Figure 2. 4. An Infrastructure based Wireless Local Area Network – Ad Hoc Network [13]

WLAN is a standardized technology which is governed by the IEEE 802.11 family of standards [14]. It offers a number of advantages over other wireless technologies. It is able to provide users with true broadband experiences at reasonable data rates. Given its perceived broadband advantages, researchers then sought to make this technology to be purely infrastructure-less to support mobility of users.

The IEEE 802.11 is a Wireless LAN standard [15] [16] [17] which operates in the 2.4GHz frequency band and it provides transmission speeds of up to 2Mbps. The standard was ratified in 1997; three years after a WLAN type wireless network was launched at the Carnegie Mellon University. The IEEE 802.11 was later extended into the IEEE 802.11a and IEEE 802.11b standards in 1999 which offered data rates as high as 54Mbps and 11Mbps respectively. The IEEE 802.11b is also known as the IEEE 802.11 high data rate and its speed matches the Ethernet speed. The IEEE 802.11a operates in the 5GHz band while the IEEE 802.11b operates in the 2.4GHz frequency band. In 2002, the best features of the IEEE 802.11a and the IEEE 802.11b were combined into the IEEE 802.11g standard which operates in the 2.4 GHz frequency band. The standard offers the raw speeds of up to 54Mbps.

The WLAN technology is the equivalent of the Ethernet local area network and is designed for resident devices. The WLAN is focused on data transmission and is not best suitable for voice due to its poor quality of service (QoS) provisioning. The WLAN technology is faster, more secure and also offers better coverage than WPAN. It is a full scale LAN network. It is easy to deploy and expand at low cost. The prizes of Wi-Fi cards are affordable. The Wi-Fi technology is economical and is a global open standard which can be implemented anywhere in the world. The technology has the highest penetration rates and is the most commonly and widely used wireless technology. The Wi-Fi technology also offers better spatial reuse than the cellular technology [18]. It is more scalable and cost effective.

2.1.4 Mobile Ad hoc networks

The WLAN technology was infrastructure based at its inception. Mobile devices would connect to the Internet through an access point (AP). The AP is a connection point which provides gateway functionality to the wired network. The AP connects user devices to the Internet backbone by means of expensive cables. WLAN provides limited mobility and it is not scalable. Furthermore, the technology does not provide the flexibility and the scalability required for communication at a very large scale.

The ad hoc network is self organising, self initializing, self healing and self managing. It is known as the mobile ad hoc network (MANET) [19]. It was designed for emergencies and for areas where wire-line systems cannot be installed; for example hazardous and historic buildings and sites.

Ad hoc networks suffer from a lot of interference which reduce network capacity. It also suffers from long transmission delays. The interference is caused by high contention on the shared medium which results in collisions. Congestions and collisions degrade network capacity and have an adverse effect on QoS provisioning. One suggested possible way of addressing this challenge, is the implementation of multi-channel MAC protocols. Multi-

channel MAC protocols reduce contention and interference by scheduling data transmission on different data channels. Concurrence improves the capacity of the wireless access networks.

2.1.5 Wireless Mesh Networks.

The WMN is structured in such a way that the benefits of both infrastructure and ad hoc modes are realised without the use of a central device or hub. It consists of a backhaul of mesh routers and an ad hoc network of mesh clients. The backhaul of mesh routers is designed to improve the capacity of the network. The backhaul also connects the ad hoc network of mesh clients to the Internet. The architecture of the WMN addresses some of the shortcomings of the IEEE 802.11 standard. For example, the ad hoc networks are not suitable for multi hop networks [20] [21], a limitation which can be addressed by the heterogeneity of mesh routers and mesh clients.

The backhaul network of the WMN is scalable and provides the much needed stability and scalability in wireless networking. More mesh routers can be deployed in the backhaul network to increase the scalability of the network and to add more redundancy which is necessary for the resilience of the network.

It is envisioned that the next generation networks will require higher data. The capacity of both MANET and WMN is not adequate and needs to be improved. Wireless access networks do not support multimedia and real time data such voice and video. Research has to focus on improving the capacity of access networks and the provisioning of QoS requirements of real-time and delay sensitive data streams.

The architecture of the WMN and its scalability is the motivation of using the IEEE 802.11 standard despite its limitation. The Distributed Coordination Function (DCF) of the standard is able to coordinate communication in an infrastructure less network. The DCF allows mobile nodes to connect to a wireless network and exchange packets in an ad hoc manner [22]. The architecture of the WMN and the use of multi-channel may reduce and eliminate most of the interference challenges of the Ad Hoc Networks.

However, the WMN should improve on fairness, channel utilization, transmission delays, scalability and throughput. The attempts to develop multi-channel MAC protocols may address some of these concerns of ad hoc networks and single channel mesh networking. Unfairness and the poor utilization of channels degrade the performance of WMN significantly. For example asymmetric views and perceived collisions challenges of the IEEE 802.11 MAC in single channel MAC protocols, cause a lot of unfairness. According to [20], disadvantaged flows can achieve 5% of throughput while privileged flows can achieve 95% of throughput in asymmetric links. In the perceived collisions domain, advantaged flows achieve 28% and 36% while disadvantaged middle flows achieve 0%. The middle flows which are the disadvantaged flows do not get a chance to transmit any packet. This unfairness can be addressed by the multi-channel MAC protocols which allow transmitters to use different channels concurrently.

2.1.5.1 Advantages of WMN

The deployment and research in WMN is motivated by good scalability, coverage and the capacity of the WMN technology. However, WMN have the attributes of multi-hop networks and they implement the IEEE 802.11 standard which is not suitable for MANET and WMN. Mesh networking suffer from reach, latency, QoS, capacity and throughput. New and innovative MAC techniques are required for WMN MAC protocols which are designed to address these limitations [23]. Mesh technology extends the coverage of "hot zones" by employing a backhaul of Mesh routers. Wi-Fi mesh networking's emphasis is on scalable hot zones instead of APs which are not scalable [23].

Mesh networking lends itself to redundancy and availability [23], the two properties which improve the reliability, robustness and resiliency of the network. The redundancy of mesh technology overcomes the problem of a single point of failure which is prevalent with the AP technology. It is also resilient to path breakages, and is self managing [24]. Furthermore, the mesh technology devices are readily available in the market and a number of mesh test beds are in operation across the globe.

Mesh networks are less mobile. They consist of static mesh routers and mobile mesh clients. They do not pose many challenges to MAC designers. For example, highly mobile networks are difficult and pose a huge challenge to MAC designers. With high Doppler effects and rapid changes in network topology and the speed of nodes, designing MAC protocols for such networks is not easy task. The mobility of WMN is a positive factor for the design of suitable and effective MAC protocols.

Mesh networking is increasingly regarded as the last mile broadband Internet access technology [25]. Mesh networks can be integrated with WiMAX technology to improve scalability. The WMN and WiMAX convergence is better known as the multi-hop WiMAX mesh network [26] [27]. The integration of mesh networks and WiMAX is also referred to as the IEEE 802.16 based wireless mesh networks. The integration of the two may address a number of capacity and throughput related challenges of wireless access networks.

WMN is cost effective and cheaper than the cellular technology. It operates on the free spectrum (2.4GHz) and its deployment is fast. The cellular technology involves the acquisition of licences and the application of sites which prolongs the deployment of the technology. Furthermore, mesh networks offer higher data rates than the cellular technology [28]. WMN perform better than other wireless technologies including the Ethernet wired network [29]. It is also reliable and easy to maintain [30]. The WMN are widely deployed in the form of test bed implementations [1]. This shows that this is a promising and a widely accepted technology.

2.1.5.2 Challenges of Mesh Networking

WMN do not guarantee reach, capacity, latency, QoS, and throughput requirements of multimedia and delay bounded data. Mesh networks have to be optimized to meet these requirements [23] [18]. Real time and multimedia data should be delivered within specified time constraints in order to meet their quality of service requirements.

The backhaul network has to forward large volumes of data up and downstream as it connects users to the Internet backbone. The shared backhaul tends to be overwhelmed by the amount of packets it has to transmit. The capacity of the shared backhaul has to be optimized for forwarded and aggregated data packets in multi hop wireless networks [24]. A backhaul offering high capacity and high data rates is ideal. As more users join the WMN and its size increase, its capacity is degraded.

The challenges of the WMN are rooted in the MAC layer. The interference challenges and scalability of the WMN can be best addressed at the MAC layer. Section 2.2 gives a detailed overview of the challenges which needs to be addressed at the MAC layer in order to improve the performance of the WMN.

2.2 The CSMA/CA protocol

The MAC layer is one of the critical layers, which affects the upper layers [22], the efficiency and reliability of data transmission. It is therefore imperative that more be done at the MAC layer to maintain and improve the QoS of access networks. The Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) MAC suffers from numerous challenges and interferences which have to be addressed to improve the capacity of the access networks [31].

The most common forms of interference are the Hidden Terminal Problem (HTP) and the Exposed Terminal Problems (ETP). It also suffers from unfairness, information asymmetry, false blocking of nodes and perceived collisions. Furthermore, IEEE 802.11 standard cannot eliminate all the instances of HTP and ETP [7] in ad hoc networks. Packet collisions degrade significantly the performance of MAC protocols [32]. The unfairness of the IEEE 802.11 standard in multi hop networks is also a concern [21]. The enhancements of the standard failed to address these interference challenges in single channel MAC protocols. The implementation of multi-channels may therefore reduce the effects of both the HTPs and ETPs, including other interference challenges discussed above.

The capacity and throughput of WMN is a challenge and is critical for the wide deployment of wireless networks. It is a fundamental performance indicator of mesh networks [33]. The capacity of mesh in the multi-channel domain can be improved through the implementation of well designed channel assignment, scheduling, selection and coordination techniques.

Mesh networking implements the IEEE 802.11 standard. The IEEE cards are readily available and affordable. As a result, a number of Mesh test beds have been established. Researchers are also considering mesh technology for wide area wireless networking [34]. This new concept is known as the Wi-Fi over Long Distance (WILD) and is deployed mainly in rural areas in India. The deployment of long distance Wi-Fi has taken a form of operational test bed, where the network is not only used for investigative purposes but also for general usage.

2.2.1 A synopsis of improvements and enhancements on the CSMA/CA

IEEE 802.11 MAC protocols do not scale well in WMN. The two models; the Point Coordination Function (PCF) and Distributed Coordination Function (DCF) are inadequate. The PCF is designed to handle delay bounded data in a point-to-point set up facilitated by a

Point Coordinator (PC), the AP. The absence of a PC in WMN makes this function irrelevant. On the other hand the DCF is contention based and leads to longer delay intervals in multi-hop environment. It degrades significantly with network size. The percentage of collisions and packet drop rates, increase significantly, eroding the available bandwidth. Bandwidth is further depleted by retransmissions and by the presence of strong interference in multi-hop environment.

The enhancements and modifications that have been proposed to improve the scalability of IEEE 802.11 DCF fall short in multi-hop and multi-channel wireless networks. The virtual sensing mechanism which employs the Reply-to-Send/Clear-to-Send (RTS/CTS) handshaking technique in conjunction with Network Allocation Vector (NAV) introduces a host of complex new challenges. RTS/CTS packets are used to notify neighbour nodes of ongoing communication sessions and to reserve the channel. Neighbouring nodes update their NAV values and back off until the channel is available. However, this handshaking technique leads to the manifestation of Exposed Terminal Problems (ETP) and Hidden Terminal Problems (HTP).

Exposed nodes are blocked, instead of promoting concurrent transmissions. This problem leads to inefficient utilization of the channel and does not promote spatial reuse. On the other hand, HTP degrades network throughput significantly. It interferes with data reception leading to packet retransmissions and exponential random back off intervals. The exponential back off intervals of the MAC protocols come at a very high cost of network performance and channel utilization.

The handshaking scheme also results in two forms of unfairness caused by the asymmetric view of the state of the network where some nodes are advantaged. The advantaged nodes know when to contend for network resources indefinitely starving disadvantaged nodes in a backlogged network. The two unfairness problems are called the Information Asymmetry (AI) and the Flow-In-the-Middle (FIM) which starves indefinitely the middle flow in backlogged flows. The middle node continuously senses the outer nodes and does not get a chance to access the channel. With carefully designed MAC protocols, this setup could be utilized as an opportunity for spatial reuse.

The introduction of multi-channel techniques at PHY has worsened the situation at the MAC level. Multi-channel communication gives rise to the deafness of the nodes, the Missing Receiver Problem (MRP) and a need to coordinate the utilization of multi-channels. The deafness of nodes in multi-channel communication underscores the limitations of virtual sensing mechanism of the IEEE MAC 802.11 protocols. In multi-channel communication, channel coordination and utilization is fundamental to guaranteeing end-to-end throughput, latency, reach and the requirements of QoS.

Multi-hop communication technique can increase throughput through spatial reuse; unfortunately, IEEE 802.11 is not optimized for spatial reuse. These problems can be arrested by a centralized approach but at the expense of performance, bandwidth, scalability and

degradation. QoS requirements are not met and an increase in throughput does not translate to minimum delays [6].

Literature has proven that a single hop, single channel IEEE 802.11 DCF is not suitable for multi-hop multi-channel systems. The IEEE 802.11e standard was later designed to combat these problems through a single hop Enhanced Distributed Channel access (EDCA) scheme and a hybrid Coordination Function (HCF). Single hop solutions are not adequate for WMN [6] [23]. Based on IEEE 802.11e, EDCF with Dual-Measurement (EDCF-DM) and adaptive EDCF were proposed in [33]. These two protocols adjust and modify contention windows. The exponential back off interval should also be reduced. Furthermore, the HTP and ETP are not solved.

Medium Access via Collision Avoidance with Enhanced Parallelism (MACA-P) scheme has also been proposed and it employs five control packets. It modifies the exponential back off interval. The use of five control packets degrades throughput. MACA-P also falls short in addressing HTP and ETP [23]. Switching in unison between transmission and receiving period to synchronize neighbour activities is a design challenge [6] [23]. Buffering further degrades the system.

The IEEE 802.11 CSMA/CA MAC protocol saturates after the third node. In [35] it has been established that the amount of throughput available to each wireless node is $(1/2) N$ (where N is the number of nodes), and it approximates to $1/N$ when the MAC is optimized. This marginal gain or increase in throughput cannot meet the needs of aggregate flows. In principle only a one hop flow is guaranteed of sufficient throughput, adversely affecting the scalability of CSMA/CA protocols in WMN. Interference, contention, retransmissions, and packet forwarding account for this low network throughput [35].

The PCF cannot be implemented in mobile access networks. The Mobile Point Coordinator (MPC) proposed in [36] does not address the heterogeneity of WMN. It also introduces a number of problems. For example, it is not easy to coordinate and manage the activities and functions of a mobile coordinator. A MPC may shut down and there may be collisions between different MPCs when their communications and movements are not coordinated [36].

The design of MAC protocols should be simple and efficient. A centralized MAC is preferred. Unfortunately on an ad hoc setup the need for a distributed MAC cannot be avoided [37]. The scheme in [37] uses inhibitive busy tones to force hidden terminals to defer their transmissions long enough to provide a collision free transmission. On the other hand CTS packets are bounded by Time To Live (TTL), while NAV can either take a RTS Defer Time (RDT) or Additional Defer Time (ADT) [27]. However, shorter durations are preferred because they address the false blocking problem.

Gaps between RTS and CTS, DATA and ACK packets can be exploited to induce parallel transmission. However it is not possible to synchronize two different transmissions in this manner. A transmitter has no prior knowledge of another transmitter and when it is scheduled to transmit; hence it cannot synchronize with it [20].

According to [21] spatial reuse can only be realized in IEEE 802.11 when the contention window is reduced. The reduction of Inter Frame Spacing (IFS) and frame length is recommended. Flow fairness should be emphasized ahead of per node fairness [21]. In [38] authors agree with [21] in the need to reduce the contention window size. However, these enhancements are not scalable. IEEE 802.11 MAC protocols should be redesigned and optimized for WMN. All these enhancements that have been effected to date fall short and do not address these challenges.

The limitations of the current IEEE 802.11 MAC and its subsequent enhancements call for the redesign and development of new MAC protocols for WMN. A scheme which is highly resistant to interference and which offers the highest possible throughput is preferred. Interference and contention are major contributors to low throughput, hence they should be addressed.

2.3 Single channel MAC protocols

Single channel MAC protocols have not achieved the desired goals. They are degraded by a single channel which is shared by a number of nodes. The shared medium suffers from high incidents of contention as a result the performance of the single channel MAC protocols are significantly degraded [39].

Single channel MAC protocols tend to block potential transmitters from transmitting [40]. The transmitters which are within the sensing range of the current transmission are forced to defer their next transmission until the ongoing transmission has been completed. These transmitters are blocked even if they are not going to interfere with the ongoing transmission. Single channel MAC protocols therefore suffer from blocking, false blocking and pseudo deadlock problems [20]. This challenge of single channel MAC protocols can be solved by multi-channel MAC protocols. In multi channel, the transmitter does not have to defer its transmission until the busy channel becomes available, but can use the next available data channel.

2.4 Multi-channel MAC protocols

Single channel MAC protocols suffer from high collisions [31]; therefore increasing the number of channels will reduce the effects of collisions and improve the capacity of the MAC protocols. However, the multi-channel MAC protocols have to address channel coordination, channel scheduling, channel assignment and network connectivity challenges. The signalling overhead cost have to be investigated and reduced in multi-channel MAC protocols which implement a common control channel. The common channel approach is network connection oriented. The MSC has to be dressed in multi-channel MAC protocols to improve performance of wireless networks.

The shared medium increases contention and degrades the performance of the network. It is envisioned that the implementation of multi-channels will address these concerns. Multi-channel MAC protocols have a potential of addressing the problems of IEEE 802.11 MAC in multi-hop networks [41]. Collision domains and the rate of collisions are likely to be reduced.

The shared medium will be de-congested through the implementation of multiple channels which allow concurrent data transmissions.

The idea to use multi-channels was first proposed in the implementation of WMN. The multiple interfaces and multiple channels approach is envisioned to reduce the interference associated with single channel MAC protocols. It was also observed that in multi-hop networks, throughput tends to decrease sharply as more hops are considered [39]. The idea of multi-channels has been an active research topic and has been considered by a number of MAC designers in WMN. The use of multi-channels is promising and positive results have been achieved. However, there are still outstanding issues which need to be addressed.

The coordination, selection, scheduling, interference, broadcasting, node deafness, network connectivity, signalling overhead and channel assignment are some of the open research issues. The introduction of multi-channels calls for the redesign and reconfiguration of MAC protocols. However, the multi-channel MAC protocols should be compatible with the existing IEEE 802.11x gadgets, which are available in the market. They should either conform to the standard or a new tailored made standard for multi-channel MAC protocols should be crafted.

The number of available non-overlapping channels is another open research area. A number of multi-channel MAC researchers assume that all the channels are orthogonal and that they have the same bandwidth. Some researchers have refuted these claims [30]. The possibility of fewer channels may not justify the implementation of multi-channels MAC protocols. It is envisioned that channel assignment, selection, coordination and scheduling techniques may address this concern and avail a reasonable number of multi-channels to justify their adoption.

Multi-channel MAC networks suffer from cross channel interference and multi-channel node deafness problem [20]. Terminals can transmit and receive on different channels. They can also listen on different channels. The problem arises when one node is trying to communicate with the other on a channel which is different from the one the target receiver is currently listening on. Such nodes will be unreachable on other channels except on those they are tuned on. This gives rise to terminal deafness problem. The deafness problem wastes network resources and degrades the capacity of the network.

The other challenge of multi-channel MAC protocols is reachability. This challenge is closely associated with the terminal deafness problem. When a broadcast packet is broadcasted on the network, it fails to reach all the terminals. This is caused by the following two main challenges. Firstly, the terminals may be busy on different channels. Secondly, a broadcast packet cannot be sent to all the channels simultaneously. It can only be sent on one channel at a time. Therefore, the synchronization of nodes and the delivery of broadcast data is a challenge in multi-channel MAC protocols.

Network connectivity is also one of the challenges, which is caused by the lack of synchronization of nodes. When nodes, for example, follow different channel hopping sequences, or listen on different channels when they are idle, they partition a network into several logical segments. Several virtual networks are created and these virtual networks are

unreachable. The reach and connectivity problems are challenges that require urgent solutions.

The common control channel approach is one of the synchronization technique which attempts to address the reach and connectivity challenges of multi-channel MAC protocols. The technique addresses these challenges albeit at high signalling overhead costs. The amount of signalling overhead should be reduced to improve the efficiency of the common control channel.

It was noted in [42] that control packet handshake constitutes up to 40% overhead. This figure is too high and it degrades significantly the performance of MAC protocols. Unfortunately, in most proposed multi-channel MAC protocols, all the control packets have been increased in size and new control packets have been proposed. This means that the control packets handshake may constitute 50% overhead or more in situations where the number of control packets has been doubled. Multi-channel MAC protocols should therefore attempt to reduce the signalling overhead of the control channel as one of the possible ways of improving the capacity and the efficiency of multi-channel networks.

The research in both mobile ad hoc networks and wireless mesh networks seeks to increase network capacity and end-to-end network throughput. The low throughput of the access networks can be attributed to the contention based IEEE 802.11 MAC standard [43]. The access mechanism of the IEEE 802.11 standard has to be reconfigured or redesigned to avail more network throughput. The multi-channel MAC approach is the promising candidate solution to these challenges. However, its efficiency and effectiveness should be improved and optimized for better performance.

Though the control channel based Multi-channel MAC protocols facilitate network connectivity; they are not efficient in channel usage. They do not utilize efficiently the available channels due to the channel assignment strategies being employed and the fact that data transmissions cannot be scheduled simultaneously to all the data channels. Data channels are placed in a queue as data flows are scheduled. The data channels are underutilized during the contention and reservation phase. They lie idle when channel assignment is being performed, and when data flows are scheduled to data channels in turns. This means that some channels are idle for extended period of time. The control channel may also lie idle when the data channels are busy transmitting data.

The under utilization of both control and data channels affects the performance of the multi-channel MAC protocols. It degrades the capacity of the MAC protocols and wastes the bandwidth. It is also envisioned that more capacity will be unlocked through the design of optimized and efficient multi-channel MAC protocols.

2.5 Summary

Multi-channel MAC protocols promise to offer a number of advantages over the single channel MAC protocols. They are likely to offer better bandwidth, reduce collisions, reduce co-channel and cross channel interference. They will also facilitate concurrent transmission

of data [5]. Mesh nodes make cooperative packet forwarding decisions, offer high bandwidth and wider network coverage. The shorter hops which are provided by mesh networks improve signal quality and QoS provisioning [44]. However, there is need for high speed, high capacity and efficient distributed multi-channel MAC protocols [45] which implement fair, efficient and scalable channel assignment, coordination, selection and scheduling algorithms.

Earliest wireless technologies were reviewed in this chapter to give a general development and advancement of mobile wireless technologies. The advancement of wireless technology and the need for mobile high speed wireless technologies led to the integration of different technologies into mesh networks. In this thesis, WMN refers to the integration of infrastructure-less WLAN (MANET) and infrastructure based WLAN technology.

University of Cape Town

Chapter 3 Review of Multi-channel MAC Protocols

3.0 Introduction

This chapter analyzes and reviews existing multi-channel MAC protocols. The MAC protocols are classified according to how they implement the control channel and coordinate multi-channels. Furthermore, the chapter highlights the shortcomings of the protocols in addressing the MSC and the signalling overhead cost.

The need for high speed and broadband networks has prompted researchers to consider wireless mesh networks (WMN) as a possible candidate for the next generation networks. The multi-channel and multi radio techniques are being considered in WMN implementation for possible strategies of achieving the anticipated higher data rates. The next generation of access networks are envisioned to offer high data rates and good quality of service. However, WMN in its current form does not meet the requirements of the next generation networks. For example, the MAC protocols are not scalable and are not optimized for multiple channels.

The IEEE 802.11 family of standards which are designed for single channel are being considered for WMN. In recent years a significant work has been done to design MAC protocols which are suitable for multi-channels and multi radio networks. In this thesis, we review multi-channel MAC schemes which implement either a temporary or dedicated control channel.

These MAC schemes are categorized into five classes namely the temporary control channel, the dedicated control channel, the contention based, the user defined and the channel hopping multi-channel MAC protocols. Furthermore, other closely related schemes will also be reviewed briefly. The main focus of the work is to show how the schemes increase the signalling overhead of the control channel. We also show how their designs fail to combat or reduce the effects of the MSC. We attest that the success and the effectiveness of multi-channel MAC protocols will depend on the reduction of the signalling payload of either the control channel or the control window. Furthermore, the schemes have to be cost effective, less complex and should address the effects of the MSC. The multi-channel MAC schemes should ensure total connectivity of the network. We also evaluate these schemes in terms of their ability to deliver broadcast packets and the amount of intelligence that is incorporated in a mobile terminal which has a limited processing power and storage capacity. Protocol intelligence refers to the ability of the protocol to acquire information for decision making.

The temporary control channel protocols are window based MAC schemes which split a communication phase into a control and data window. Data channels are reserved during the control window through the control channel. However, the schemes under this category do vary in the implementation of the control channel.

The multi radio schemes employ two radios, a control channel radio and a data channel radio. The data channels may be user defined or contention based. The data channels radio switches between data channels or stay on a user defined channel for a set duration of time. The

control transceiver transmits control packets while the data channel transceiver transmits data and acknowledgement (ACK) packets. The dedicated control MAC schemes implement a single transceiver which switches dynamically between all the available channels. Data channels are reserved through the control channel; thereafter the terminals have to switch onto the reserved data channels to transmit data packets.

3.1 Classification of multi-channel MAC protocols

There are many different ways in which the multi-channel MAC protocols can be classified. They can be classified according to their function, design or according to their main objectives which they seek to achieve. In this Section, we classify the multi-channel MAC protocols according to the number of transceivers they employ and the way data channels are reserved. The common aspect of these protocols is the implementation of a control channel; as a temporary or dedicated control channel. There are many other multi-channel MAC protocols of interest which do not implement the idea of a control channel. Some of these protocols will be discussed briefly under the channel hopping category in Section 3.1.5. The focus of the thesis is on the implementation of the control channel and the effects of its payload on the performance of multi-channel MAC protocols. We also show how these MAC protocols are affected by the MSC.

Fig. 3.1 depicts the five main classifications of Multi-channel MAC protocols. These are the temporary control channel, the dedicated control channel, the contention based, the user defined and the channel hopping multi-channel MAC protocols. This classification serves the purpose and the objective of this thesis which seeks to evaluate the impact of both the control channel overhead and the MSC on the capacity of the control channel as well as the capacity of the multi-channel MAC protocols.

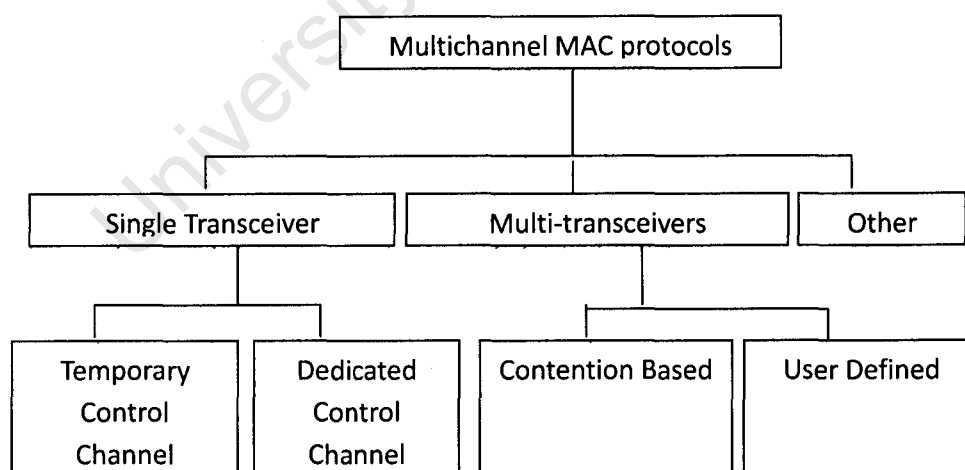


Figure 3. 1. The classification of Multi-channel MAC protocols.

The temporary control channel MAC protocols are window based multi-channel protocols which employ one channel as a signalling channel only during the reservation of data channels inside the control window. Inside the data window, the control channel is used as a data channel. This is in contrast to MAC protocols that employ a dedicated control channel.

The dedicated control channel is permanent and is used for the entire lifespan of the network and never used for the transmission of data frames. On the other hand multi radio MAC protocols can either be classified as user defined or contention based multi-channel MAC protocols.

Multi radio multi-channel MAC protocols employ a notion of a control channel; however, they differ in data channels selection and coordination. The user defined protocols assign a data channel to a specific terminal while in the contention based protocols all the data channels are available to all the available terminals. The terminals are expected to contend for data channels when they have data frames to transmit. A data channel is assigned to a sender/receiver pair to transmit data. Nodes have control over the data channel only during data packets exchange. After the transmission of data packets, the data channel is released for use by the next pair. Lastly, in Section 3.1.5, multi-channel MAC protocols such as the split phase, and channel hopping algorithms are evaluated.

3.1.1 Contention based multi-channel multi radio techniques

In this Section, we evaluate the multi-channel MAC protocols which employ two radios. One radio is tuned permanently on the control channel and the other radio switches dynamically between the data channels. The terminals contend for the data channels and reserve them through the control channel with the aid of data structures. The data structures mainly keep track of all the busy data channels and list all the idle data channels to assist terminals in reserving data channels.

In [7], a multi-channel MAC protocol called the Dynamic Channel Assignment (DCA) is proposed. The paper is one of the earliest research works in the area of multi-channel MAC protocols. The DCA scheme implements two transceivers, one control channel and n data channels. One transceiver is tuned permanently on the control channel while the other transceiver switches dynamically between the available data channels. The control channel is employed for signalling purposes. Terminals contend for access to the control channel using the Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) access protocol to reserve one of the available data channels. The control packets, Request to Send (RTS), Clear to Send (CTS) and the Reserve (RES) are transmitted on the control channel. The data frames and the ACK packets are transmitted on the available data channels.

All the data channels are assumed to be of equal bandwidth, and nodes switch dynamically between data channels. Unfortunately, in multi-channel environment nodes incur a switching cost of up to $224\mu\text{s}$ [1] [46]. If a node switches regularly, the switching cost may degrade severely the performance of the protocol.

Data channels are reserved through a data structure called the channel usage list (CUL). Each node is expected to maintain and update its CUL every time it overhears a control packet on the control channel. The RTS packets will also include the free channel list (FUL), a list of channels which are available for use in the sender's communication zone. Upon receiving the RTS packet, the receiver has to check its CUL against the sender's FUL data structure. If there is a common data channel available at both sender and receiver, the receiver will select

the free data channel and send a CTS packet to the receiver. The receiver further sends a RES packet to reserve the selected data channel.

The RES packet is an additional control packet which was first introduced in the DCA protocol. The introduction of this RES packet causes longer signalling delays which degrade the performance of the control channel. The capacity of the control channel should be improved and signalling delays be reduced. Furthermore, the RES packet fails to inhibit hidden terminals which are in the communication range of the receiver.

The proposed DCA does not provide a solution to a scenario where a common free channel is not available. It assumes that there will always be a free channel on both the sender and receiving nodes' communication zones. The protocol is complex and too expensive in terms of hardware cost. The use of two transceivers increases the hardware cost of mobile devices. Lastly, a mobile device with two transceivers suffers from signal leakages, where signals from the two transceivers interfere with each other.

The bandwidth of data channels is underutilized during the reservation phase. The data channels lie idle and their bandwidth is not utilized to improve end to end throughput. The data channels are subjected to multi-channel scheduling cost in which they lie idle in each phase waiting for their next data transmission. The control channel cannot schedule data transmissions to all the data channels simultaneously. Some data channels have to wait for long durations before they are reserved. The under-utilization of the capacity of data channels while they wait in the scheduling queue is called the MSC. Unfortunately, the MSC is repetitive and has a significant effect on most multi-channel MAC protocols.

A similar protocol with minor variations is proposed in [47]. This protocol variation is best described as DCA with power control. It is designed to solve the following: the channel assignment, medium access and the power control challenges. Data channels reservation is done through the exchange of RTS/CTS/RES control packets with the aid of the channel usage list (CUL) and the free channel list (FCL) data structures. The setup and functionality of the protocol is similar to the scheme proposed in [7]. It also suffers from long control channel signalling delays, the signal leakage problem, complexity and high hardware costs. The capacity and performance of the multi-channel MAC protocols can be improved by reducing the control channel signalling delays and overhead costs.

A kernel based scheme is proposed for multi-channel systems with multi-interfaces in [48]. The interfaces are fewer than the channels; hence the need for interfaces to switch between the channels. The word interfaces is synonymous with multi-radios. In the proposed scheme, the interfaces incur a switching penalty of 5ms. It was noted that frequent interface switching would degrade significantly the performance the protocol. A new channel abstraction module was added to offer a virtual switching mechanism. The channel abstraction module resides between the network layer and the interface device drivers. This channel abstraction module was designed to reduce the interface switching penalty.

Since each node is equipped with two interfaces, one interface is permanently tuned on one fixed channel and the other switches between the remaining channels. Nodes select different

fixed channels. These fixed channels are advertised using broadcast *hello* messages. Each node has to advertise its fixed channel for other nodes to know its selected channel which they should use to communicate with it. The fixed channels differ and nodes are free to select any channel of their choice. The selected fixed channels can be changed from time to time. However, the scheme tries to balance the number and the use of fixed channels at any given instance.

The use of broadcast hello messages to advertise node's fixed channel wastes a lot of bandwidth. These broadcasts are sent on all channels to reach all the nodes. Some nodes may not receive the broadcast hello messages due to the missing receiver problem and the logical portioning of the network given user preferred fixed channels which are different and the frequency at which they are changed.

All the nodes are required to keep a unicast table to record the fixed channels of their neighbours. Mobile nodes have a limited processing power and storage capacity. This may compromise their capacity and functionality.

In [49] and [50], protocols similar to one in [48] are proposed. The limitations observed and discussed in [6] are also applicable to [49] and [50].

The paper in [51] proposed a multi radio multi-channel scheme. A single channel is set aside as a control channel and the rest of the channels are earmarked for data transmission. The protocol uses a data structure called a channel list (CL) for all data channels. The CL is used for data channel reservation. The scheme suffers from the signal leakage problem caused by radios transmitting close to each other. It is also not clear how the use of multi-radios is coordinated. Nodes are allowed to reserve channels which are currently in use. The nodes are required to defer their transmissions on these data channels until they become idle. Unfortunately, the protocol requires nodes to do a lot of processing and coordination. Mobile nodes have limited processing and storage capacity and may not cope with the load to be processed.

The scheme proposed in [52] implements multi interfaces and multi channels. It is assumed that a node can switch between a send and a receive mode on a call by call basis. The common control channel is referred to as the control interface. The control interface is designed for the transmission of broadcast HELLO packets. The data channels are referred to as the data interfaces. The following: RTS/CTS/DATA/ACK packets are transmitted on the data interface which worsens the MSC.

A number of multiple channel and multiple radio techniques assume that broadcast packets can be delivered to all the available nodes within the same time frame. However, this is not possible given the fact that nodes may be on different channels when broadcast packets are sent. This fact was noted in [53] where broadcasting and broadcast latency was analyzed in multi-channel and multi-radio schemes. The paper analyzed the broadcast latency in multi radio multi-channel networks and noted that it is a design challenge caused by channel selection algorithms and nodes communicating on different channels.

The proposed protocol in [8] employs two network interfaces and was designed to reduce the channel negotiation cost. The proposed scheme is called the Connection-Oriented Multi-channel MAC (CO-MMAC) protocol. It divides system bandwidth into one control channel and into n data channels. The channels are assumed to be of equal bandwidth and that they are non-overlapping. The control packets, RTS, CTS, and RES are transmitted on the control channel including the broadcast packets.

Nodes maintain two tables, a Neighbour Status Table (NST) and a Channel Status Table (CST). A node records all the channels used by its neighbours in its NST. It also records all the data channels information overhead on control packets in its NST table. The CST is used to record the Network Allocation Vectors (NAV) of data channels. The information required to update both the NST and the CST is contained in the RTS, CTS and RES control packets.

The nodes' tables will be updated albeit at high cost of hardware and complexity given the two network interfaces. The protocol also suffers from signal leakages owing to two network interfaces placed close to each other.

The proposed RTS is 24 bytes long, 4 bytes longer than the current RTS packets. The proposed CTS packet is also longer than the conventional one by one byte and it is now 15 bytes long. The protocol also makes use of a new packet called the RES packet which is 16 bytes long. The new RES packet together with the proposed RTS and CTS packets degrade the bandwidth of the control channel. They also increase the channel negotiation cost by incurring higher control channel overhead costs due to longer transmission durations of the three packets.

Despite the use of two network interfaces, the scheme also suffers from the MSC which is repetitive. Significant bandwidth is under-utilized due to MSC which is caused by the inability of the control channel to schedule simultaneously data transmissions to all available data channels. Furthermore, data channel network interfaces are subjected to multi-channel switching delays and are also underutilized.

The protocol does not consider multi-channel switching penalty and the timeouts of the control packets are set to trigger at the end of the ACK transmission. This worsens the effect of the Multichannel scheduling cost. The timeouts should be reconfigured and optimized taking into consideration the fact that the control and the data channels use two different network interfaces. The readjustment of the timeouts reduces the MSC and the signalling overhead of the control channel. However, the use of status tables in data channels reservation reduces the carrier sensing duration.

The scheme in [9] employs multiple interfaces, a common channel and data channels. The common channel is used for channel assignment and the other channels which are called the traffic channels are set aside for data and ACK packets transmission. Every node maintains a traffic channels usage table which is updated using information overhead on the common channel. The common channel can also be used as a traffic channel when its traffic is low. On the other hand, if a node is aware of the destination's traffic channel, the control handshake will be performed on a given traffic channel. These packets are not heard by other nodes as a

result, other nodes will fail to update their traffic channel usage tables. Nodes in general use information overheard on the common channel to update their tables.

The protocol introduces six more control packets which increase significantly the payload of the control channel. The additional packets are the Negative clear to send (NCTS), Request to find/acknowledgement to find (RTF/ATF), Request to change traffic channel/acknowledgement to change traffic channel (RCT/ACT), and NAV broadcast (NBC). The scheme is also complex and expensive in terms of hardware costs due to the use of two transceivers. The MSC is also too high due to high signalling cost owing to too many control packets. The control packets take up a substantial amount of bandwidth as a result the utilization of traffic channels is low and not effective.

The traffic channel transceiver listens on one traffic channel until it has data to send on a different traffic channel or when the current traffic channel becomes saturated. However, a change in traffic channel should be advertised on the common channel through broadcast packets. The use of broadcast packets increases overhead costs and complexity of the protocol. Delays may be incurred while a node contends for the common channel to advertise its intention to change its traffic channel. The broadcast packets cannot reach all the nodes which are on different traffic channels.

When the nodes have full knowledge of each other's traffic channels, the common channel and the common channel transceiver will be underutilized since nodes will use the traffic channel transceiver to communicate directly with their destination nodes on a given traffic channel. This will also make it difficult for joining nodes to acquire information about their neighbours and to update their neighbour tables.

In the event of NBC messages being destroyed due to packet collisions, the protocol will be highly unstable and communication will be impossible. Nodes' neighbour tables will not be up to date and packets will be sent on wrong traffic channels resulting in high incidences of node deafness problems. The scheme also employs a channel assignment and channel reassignment algorithm which increases the payload of the protocol and introduces more signalling delay related costs.

The main challenges of the multi radio systems are complexity and cost. They also waste a lot of bandwidth on both the control and data channels. They suffer from the multi-channel scheduling cost which is repetitive. The MSC is caused by a single signalling channel which schedules one data transmission at a time to one data channel while the other data channels lie idle. The control channel of the proposed protocol is idle when data channels are transmitting data. On the other hand, when the control channel is busy, data channels are idle waiting for nodes to reserve them. After the pair has reserved a data channel, the data channel radio may have to switch onto the reserved data channel and therefore increasing the effect of the MSC. For example, Fig. 3.2 shows how the multi-radio MAC protocols under-utilize the bandwidth of both the control and the data channels.

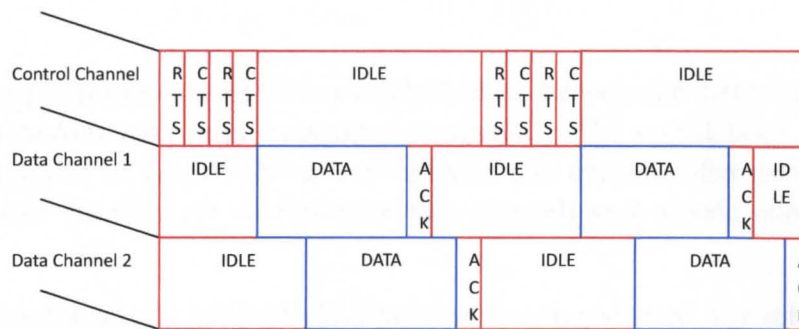


Figure 3. 2. The impact of multi-transceivers on the utilization of channels

The top row in Fig. 3.2 depicts the control channel. The middle and the bottom rows are the two data channels. For simplicity, only two data channels were chosen otherwise more data channels can be considered. As shown in the figure all the channels have busy and idle durations. Nodes will first exchange the control packets on the control channel to reserve the available data channels. The nodes will then switch onto the reserved data channels while the control channel remains idle until the nodes have switched back onto it. The data channels lie idle during the exchange of RTS/CTS packets on the control channel. On the other hand, nodes incur two channel switching delays, when they switch from the control channel to the data channels and thereafter back to the control channel. However, the switching durations were not highlighted in the diagram. The two channel switching delays increase the idle durations of both the control channel and the data channels.

In Fig. 3.2, it can be seen that these idle slots are recurring after every cycle. A significant amount of bandwidth is wasted due to these repetitive idle slots on all the channels. This challenge has been termed the Multi-channel Scheduling Cost. It is caused by the reactive approach to scheduling data transmission on data channels.

The data channels are reserved when they are free and when the current nodes have switched back onto the control channel. The timeouts are designed such that all nodes overhearing the control packets can set their NAV values to expire at the end of data transmission. Unfortunately, data transmission in multi-channel networks includes two channel switching delays. Hence there is a need for a proactive data channels reservation mechanism which reduces the MSC. Two possible solutions are to reserve a data channel before the current transmission is completed, or to reduce the amount of control channel signalling overhead. The two techniques can be combined to reduce or eliminated the multi-channel scheduling cost.

The MSC requires a good scheduling and data channel coordination strategy which can improve the utilization of data channels. More bandwidth can be unlocked by solving the MSC challenge which in turn may improve the scalability of multi-channel MAC protocols.

3.1.2 User defined multi-channel multi radio techniques

The functionality of multi radio multi-channel MAC protocols can also be classified as user defined in which nodes select home data channels. The nodes select their fixed data channels and broadcast their selection inviting other nodes to use their selected data channels. In the

previous technique, nodes contend for any available data channels and thereafter release them after the data packets have been transmitted successfully. The user defined multi-channel multi radio protocols on the other hand retain selected data channels after data transmission. The selected data channels are used as home data channels until a node selects a different data channel.

In [10], a multi-channel and multi-interface MAC scheme is proposed. The scheme proposes the use of multiple interfaces in combination with channel assignment and routing techniques. The scheme is designed to use multiple channels and multiple interfaces effectively. Unfortunately, the scheme does not ensure total network connectivity and it partitions the network into several segments. Nodes listen on different channels and tune on different interfaces thereby segmenting the network logically. Furthermore, it is not feasible to have many interfaces on a single mobile device. Lastly, when interfaces are installed on one device, they interfere with each other when signals leak from one interface to the other.

A hybrid channel assignment scheme which does not require clock synchronization is proposed in [54], [55] and in [2]. The schemes employ one fixed interface and one switchable interface. They integrate both the static and the dynamic channel assignment strategies into one strategy called the hybrid approach. The static approach is employed to solve the rendezvous problem to ensure that nodes can synchronize. The dynamic approach is employed in the utilization of channels. The objective of the dynamic approach is to improve the effective use of multiple channels.

The schemes also implement multiple queues, a queue for each channel. The switchable interface has to stay tuned on one channel for a set period of time to transmit packets for a given data channel queue. The implementation of the multiple queues requires more processing power and disk space, which is a challenge for mobile nodes. Furthermore, the scheme introduces unfairness as it transmits packets for one queue for a set period of time. It is not sensitive to delay bounded packets. Data frames in the next queue are only transmitted after the expiry of the transmission timeslot of the current queue. The deferment duration is very long and degrades the performance of the protocol.

The introduction of Dynamic Staying Time (DST) and Fixed Staying Time (FST) though novel, require a lot of processing and knowledge of all queue lengths which degrades the performance of the scheme. The dynamic waiting time also requires more processing time to set a value for a given channel. The functionality of the scheme also depends on the collision probability unfortunately, this probability is approximated. The actual values are not used.

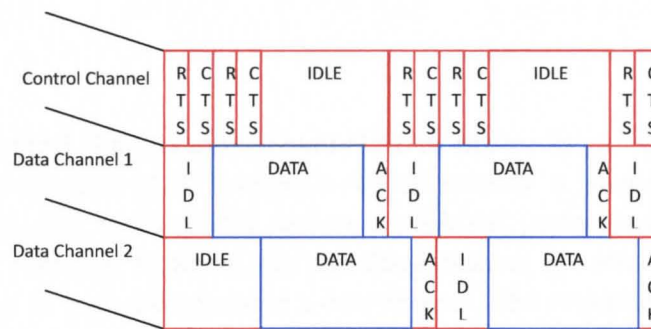


Figure 3. 3. The impact of the Multi-channel Scheduling Cost in user defined multi-channel multi-radio MAC protocols.

The user defined multi-channel multi radio MAC protocols are similar to contention based multi-channel multi radio MAC protocols. However, they do differ in the selection of data channels and in the release of selected data channels at the end of data transmission. In contention based protocols, nodes reserve a data channel through the control channel with the aid of data structures stored on individual nodes. When the data channel has been reserved nodes have to switch to the data channels before transmitting the data packets. The data channel is released after data transmission.

The user defined class of MAC protocols retain the data channel after transmission and there is no need to switch to a reserved data channel because user defined data channels are fixed. The data channel transceivers do not switch between channels during data transmission. They only switch when a node selects a new fixed data channel after a set period of time. Therefore, there is no need for frequent channel switching hence the effect of the MSC is minimized. However, the missing receiver problem and network connectivity are of concern.

In Fig.3.3, we have the top row depicting the control channel which transmits the control packets and the bottom two rows representing the two data channels which transmit data and ACK packets. The data channels lie idle while the nodes are busy on the control channel reserving data channels. When the nodes switch onto the reserved data channels, the control channel remains idle. The idle slots degrade the capacity of the control and data channels. However, the implementation of user defined data channels reduces the effect of the MSC on data channels.

The multi-channel multi radio protocols waste a lot of bandwidth on both the control and data channel. Their effectiveness in the utilization of the control and the data channels does not justify the use of multiple radios. There is need for a trade off between the cost of hardware and channel utilization which may improve the capacity of the control channel and the performance of the scheme in general.

The design goals of MAC protocols should not be optimized for increased end to end throughput at the expense of efficiency. Throughput is the average rate of packets received. The efficiency of the protocol cannot be sacrificed for expensive techniques such as multiple radios schemes. An optimal mapping of the number of channels to transceivers is desired. The optimal number of channels that can be supported effectively by a single transceiver should therefore be established. Thereafter such results can enable MAC designers to cascade and scale up MAC protocols in a more scalable and effective manner.

3.1.3 Temporary Control channel multi-channel MAC protocols

In this section, multi-channel MAC protocols which employ a single transceiver are presented and analyzed. The focus of this section is on MAC protocols that set aside one channel for signalling purposes. However, the signalling channel can also be used as a data channel. Thus, it serves as both a control and a data channel. The communication process is divided into two windows, the control and the data window. The control channel is used as a signalling channel inside the control window and thereafter as a data channel during the data window. During the data window, nodes reserve the data channels. Once the control window session has ended, nodes start transmitting data frames on the reserved data channels during the data window.

The detailed descriptions of these protocols are discussed in the sequel. The shortcomings and the strengths of these protocols are also reviewed. The emphasis is on how the design and functionality of these protocols affect the capacity of the control channel, which is considered as the driver of multi-channel MAC protocols. The analysis also shows how these protocols increase the effects of the MSC.

The Extended Receiver Directed Transmission protocol (xRDT) in [4] is one of the multi-channel MAC protocols which implement a temporary control channel. The xRDT employs a temporary control channel which is referred to as the quiescent channel. The protocol makes use of dedicated busy tone channel to coordinate the access of nodes to data channels. The scheme requires an additional transceiver tuned on the dedicated busy tone channel. A node which wants to use a given channel has to first sense the corresponding busy tone channel for busy tone signals. If the busy tone channel is sensed as busy, the node has to defer its transmission, but if it is free, the node contends for the data channel.

All the nodes in the xRDT protocol have to select quiescent a channel to listen on when they are idle. The quiescent channels serve as the home channels of the nodes. Nodes switch from quiescent channels onto reserved data channels to transmit data. They then return onto their respective quiescent channels after data transmission. When the nodes return to their quiescent channels they broadcast Data Transmission Messages (DTM) to register their availability. The DTM is an invitation to nodes which were waiting for the return of a given node to its quiescent channel to initiate communication with it. Every node upon its return anticipates that there are nodes which want to send packets to it. As a result, nodes flood the network with DTM and degrade significantly the performance of the network. A lot of bandwidth is wasted when the network is flooded with data transmission messages.

The other shortcoming of the proposed protocol is its reservation mechanism which allows a receiving node to reserve a data channel. The receiving node can only notify nodes in its communication zone about the reserved channel. The nodes which are hidden to it are not inhibited. The hidden nodes will interfere with data reception and data packets may be destroyed prompting nodes to retransmit packets further degrading the performance of the protocol.

The selection of quiescent channels is done periodically. It is based on the load of data channels. A data channel with the least load is selected. Communication with a node takes place on its quiescent channel. The xRDT protocol sends busy tone signals in the place of CTS and ACK packets. Furthermore, broadcasted packets cannot reach all the nodes which are currently listening on different quiescent channels.

Maheshwari et al [4] also proposed a second protocol called the Local Coordination-based Multichannel MAC (LCM MAC). The LCM MAC was designed to address the shortcomings of the xRDT. In the LCM MAC data transmission is preceded with control and data windows. Control packets are sent on a common channel during the control window and data packets are sent on all the channels during the data window. The channel which was set as a control channel during the control window is used as a data channel inside the data window to transmit data. The common channel is employed as a signalling channel and is known as the default channel during the control window.

Data channels are reserved during the control window. Therefore, nodes switch to the data channels to transmit their packets. In the control window only one channel is utilized, the default channel. The data channels lie idle and their bandwidth is wasted during the control window. More bandwidth is also wasted when the nodes switch on the data channels from the control channel after the control window. Furthermore, nodes have to take turns to transmit on the reserved data channels. This means that some nodes will defer for longer periods during the data window waiting for their turn to transmit their data. The protocol allows more than one pairs to reserve one data channel during the control window. The nodes are then scheduled to take turns to transmit data during the data window.

The LCM MAC first selects a master node to coordinate the reservation of data channels and the transmission of data. This master node is expected to first advertise control and data window schedules through the RTS. The RTS length has been increased to accommodate the additional fields to store the control and data window durations. The additional fields degrade the performance of the scheme. The RTS also stores a list of all data channels which are free at the sender. When the receiving node receives the RTS packet, it replies with a CTS packet and selects the identity (ID) of the channel which is free both at the receiver and sender.

The selected data channel is reserved by the nodes and is be used for the exchange of data packets during the data window. The CTS has an additional field to store the channel ID which further degrades the performance of the proposed protocol. When the sender receives the CTS packet, it sends a RES packet to reserve the data channel. The RES packet contains the transmission schedule and the channel ID. Overhearing nodes use the information contained in the RES and CTS packets to update their Multi-channel NAV values. The RES packet is an additional packet which degrades the performance of the control channel.

The protocol does not provide any mechanism of ensuring that only one master node publishes control and data windows. If a number of nodes that are within the same communication zone or overlapping zones publish the control and the data windows, there will be high chances of data collisions.

In [2], a scheme employing a common default channel is proposed. The scheme relies on the services of a data structure called the Preferable Channel List (PCL) to coordinate the reservation of data channels. The reservation of data channels is done during an ATIM window on the default channel. That is, the default channel is only implemented during the ATIM window. In the data window the default channel is used as a data channel.

The sizes of the ATIM and ATIM-ACK packets have been increased to cater for the channel information. Unfortunately, the increased packet sizes degrade the performance of the protocol. The scheme also introduces a new packet called the ATIM-RES which also impact negatively on the performance of the system.

After channel negotiation, the communicating pair switches on to the reserved data channel to exchange the RTS and CTS packets before sending any data packets. The signalling overhead cost is too high. Signalling takes place on both the default channel during the ATIM window and on the data channels during the data window resulting in a worst case scenario in the context of the MSC. Both the control and the data channels suffer from the MSC. Furthermore, when the nodes fail to agree on one channel, data transmission is deferred until the next beacon interval. Unfortunately, the nodes would have already wasted the resources.

The scheme uses the CSMA mechanism in sending both the ATIM/ATIM-ACK and the RTS/CTS packets which wastes a lot of resources. During the ATIM window a data channel can be reserved by many nodes. The nodes will then contend for the same data channel using the RTS/CTS packets. There is a possibility that a pair may fail to access a data channel during the data window, which it had reserved in the ATIM window. When this happens, bandwidth is wasted. More bandwidth is wasted during the ATIM window when all data channels are not utilized. The bandwidth is further depleted when RTS/CTS precedes the transmission of data frames on the data channels.

The implementation of a temporary control channel is also proposed in [56]. One channel is set aside as a signalling channel and is referred to as a dedicated channel. The rest of the channels are set aside as data channels. The dedicated channel can also be used as a data channel when the contention period has ended. The protocol is divided into a contention reservation interval (CRI) and contention free interval (CFI). Nodes contend for network resources and data channels during the CRI. Thereafter, they all defer their transmissions until the CFI. The deferment of data transmission wastes resources and degrades the capacity of the dedicated and data channels. The protocol also requires global synchronization, a challenge for mobile wireless nodes.

The data channels lie idle during the CFI hence their bandwidth is not utilized effectively. This is a common problem with all protocols which divide a transmission process into contention and data transmission windows. They create the worst case of the MSC.

Nodes in [57] randomly select home channels to listen on when they are idle. The proposed protocols segment a network and not facilitate network connectivity for effective communication.

Each node independently and randomly chooses a home channel which it listens on when idle for incoming packets. At start-up, nodes sense all the available channels to discover neighbours and add them to their neighbour tables. The process of updating neighbour tables is costly as nodes incur both very high channel switching and sensing costs.

A new node can also send broadcast packets to probe neighbours. Broadcast packets flood the network and increase chances of data collisions. There is also a possibility that many nodes may not receive the broadcasted packets since they will be listening on different home channels. The responses to probing broadcast packets are also susceptible to interference and collisions.

The paper does not explain how a joining node will broadcast its probing packet on one channel yet the packet is meant to be received by nodes on different channels. Before sending data, a node has to first determine the home channel of the receiver then switch onto it. The node then contends for the destination node's home channel. Nodes experience longer signalling delays before they send out their data packets. Unfortunately, the process of determining the recipient's home channel is not described.

Wen-Tsuen Chen et al [58] proposes a single transceiver Multi-channel MAC protocol which implements contention and data windows. The size of the contention window is not fixed; it is adjusted using smart window increase and decrease rules. The smart concept is not described. The control channel is used for data channel reservation. A three way channel reservation handshake is implemented with an additional control packet called the Multi-channel CTS Recognition (MCTS-R). The MCTS is used by the sender to confirm the channel reservation. The protocol does not consider the channel switching delay. Channel switching delay cannot be avoided in a multi-channel network.

The following packets are exchanged during the control window to reserve a data channel: MRTS, MCTS and MCTS-R. The MRTS and MCTS packets are also exchanged by nodes on the data channel before they transmit data frames. There are too many signalling packets that are exchanged by nodes. These packets increase the signalling overhead cost of the proposed protocol and degrade its performance and the capacity of the control channel. They also worsen the effects of the MSC. There is a need for the reduction of signalling overhead on the control channel to improve its scheduling capacity.

The protocol also employs the use of data structures in data channel reservation. Each node keeps the following data structures: the In-use channel and two channel lists called the free channel list and busy channel list. The in use channel, is the channel which has been selected by the node for use. The free list is a list of channels which have not been selected by the neighbours of a given node. Lastly, the busy channel list is the list of all the channels selected as in use channels by the node's neighbours. A counter is maintained to sum up all the channels in the busy channel list, and the number of nodes which have selected them.

The data channels are not used during the control window and their bandwidth is wasted. There is need to utilize the channels effectively to reduce the MSC and increase the capacity of the control channel.

The Group Allocation Multi hop Multiple Access (GAMMA) in [59] implements multiple transmission channels. Each transmitter has a unique channel. Nodes first join a transmission-group before they can initiate any transmission. Once the terminal has become a member of a transmission group, it can send all its data frames to the receiving node. The node has to send all its packets once it has been given the right to do so. The nodes do not contend for the channel and there is no interference during the transmission of data frames. Unfortunately, the proposed scheme is not connection-oriented. It creates a number of logical sub networks, which may lead to a high incidence of MRP and hidden terminals. The node deafness and the hidden terminal problem degrade the capacity of the network. A significant number of packets may be retransmitted which degrade the performance of the protocol.

The GAMMA protocol divides the transmission channel into cycles. Each cycle is divided into contention and data slots. A station sends an RTS and receives a CTS packet during the contention slot. The RTS/CTS packets are sent when a node wishes to register with a transmission group. Once it has been registered, it is issued with a data slot to transmit all its packets. A node can also receive its data packets during this data slot. However, this approach tends to be wasteful if a node has no data to receive and fewer packets to send.

Nodes can have different cycle lengths while their contention slots have to be aligned for nodes to exchange successfully RTS/CTS packets. This calls for synchronization which is a challenge. The source and destination nodes should be synchronized in a slot which is a challenge for wireless networks. The challenge is worsened by the difference in the lengths of transmission cycles. Interestingly, according to the authors, if cycles are not equal, or are equal but shifted or misaligned, the nodes will not be able to exchange data.

A node with a shorter cycle adds additional data slots, which waste bandwidth. Furthermore, the decision to add more data slots should be communicated to group members. The details about the increases of data slots are captured in data and ACK packets headers. All the nodes which overhear the data and ACK packets are expected to also increase the lengths of their cycles so that they are aligned with the node which initiated the changes in the data slots sizes. The process of realigning data slots degrades the performance of the protocol. More bandwidth is wasted through the realignment of data slots.

Data and ACK packets also contain a flag in their headers which informs neighbouring nodes when a station is likely to reduce its cycle length. The packet headers also contain additional information on cycle lengths and cycle length flags. When a node has reduced its data slot size, its neighbours are also expected to reduce their data slots by the same margin for the realignment purposes. These decisions should be communicated to all neighbours which increases substantially the payload of the protocol. The proposed protocol is also complex.

Nodes attach information about their cycles, the number of data slots, and the unallocated data slots to data and ACK packets headers. The packet header sizes should be increased to accommodate additional information. The enlarged data and ACK packets degrade the capacity of the network. The cycle information is also sent to neighbours when new stations join a group triggering the need to resize data slots and to realign them.

A node can leave or deregister from a group if it does not have data to send or receive. It has to set an appropriate flag in its packet header and should inform the destination node about its intention to deregister before it leaves the group. The membership of nodes can also be lost if a number of its data slots remain idle for a number of successive cycles. Unfortunately, significant amount of bandwidth would have been wasted already before a node with idle data slots is removed. The node also waste bandwidth when it registers its intention with the destination node to leave a group.

The multi-channel MAC protocols in this category, in general, split a communication session into control and data windows. The reservation of data channels is done inside the control window through a temporary control channel. The bandwidth of the data channels is not utilized during the control window. All the data channels remain idle in the control window until the reservation of data channels has ended. The control channel is utilized as a data channel in the data window. The bandwidth which is wasted during the control window should be harnessed to increase the capacity of the network and to improve the effectiveness of these protocols. The wasted bandwidth is caused by the MSC which needs to be addressed by employing appropriate scheduling techniques which minimize its effects.

The MSC is the dominant problem in Multi-channel MAC protocols owing to the failure of the single signalling channel to schedule simultaneously data transmissions to all the available data channels. The MSC may be solved by improving the utilization of channels and by improving the capacity of the control channel and its scheduling capacity.

	Control Window	Data Window	Control Window	Data Window
Control Channel	Reservation	Data Frame	Reservation	Data Frame
Data Channel 1	DATA IDLE	Data Frame	DATA IDLE	Data Frame
Data Channel 2	DATA IDLE	Data Frame	DATA IDLE	Data Frame

Figure 3. 4. The poor utilization of data channels in window based multi-channel MAC protocols.

Fig. 3.4 shows the functionality of multi-channel MAC protocols which implement a temporary control channel. The protocols divide a communication process into control and data windows as shown in Fig.3.4. The reservation of data channels is done during the control window. The data frames are transmitted during the data window.

In Fig.3.4, each column is marked either as control window or data window. The rows represent the channels. The top row represents the temporary control channel. Inside the control window, the control channel is marked "Reservation" while in the data window it is marked "Data Frame". This shows that the control channel is used for data channel reservation during the control window and then as a data channel inside the data window to transmit data frames.

The last two rows depict two data channels. When data channels are being reserved during the control window, they lie idle and remain unused until the end of the control window. The

bandwidth of the data channels is wasted during each and every data channel reservation phase in the control window. The protocols are very effective in utilizing the channels during the data window and there is no channel which lies idle inside the data window.

The elimination or reduction of the idle periods of data channels during the control window which is repetitive can solve the MSC and utilize bandwidth efficiently. The scheduling capacity of the control channel can also be improved when the MSC is reduced.

3.1.4 Dedicated Control Channel multi-channel MAC protocols

The multi-channel MAC protocols in this category employ a single transceiver and one dedicated control channel. The control channel is used exclusively for signalling purposes. The rest of the channels are earmarked for data transmission. The protocols also suffer from the MSC as a result of the poor utilization of the channels. However, the MAC protocols in this category do facilitate network connectivity. They provide nodes with a common reference point, the control channel on which all nodes listen on when they are idle. The control channel therefore helps in the synchronization of nodes.

The control channel is the driver of these MAC protocols. It can either improve the performance of the protocol or degrade it depending on its design. If the control channel has limited capacity it may cause a system bottleneck. On the hand, if it is well designed and has enough capacity it can improve the performance of the network. The amount of signalling should be reduced to improve the capacity of the control channel. We review the effectiveness of the MAC protocols in this section in reducing the signalling overhead. It is envisaged that the reduction of the signalling overhead may improve the performance of the MAC protocols implementing a dedicated control channel.

Luo et al [60] introduces a concept of a distributed information sharing scheme, to ensure that communicating pairs do not make independent decisions. Neighbouring nodes can notify a transmitter-receiver when they perceive a conflict. Unfortunately, there is no effective solution given to solve collisions that will be caused by simultaneous notifications. The neighbouring terminals can also notify transmitters intending to communicate with missing receivers to defer transmissions to deaf nodes.

The proposed protocol does implement a dedicated control channel. However it is optimized to solve the terminal deafness problem and collisions on data channels. The proposal also analyzed the single control channel bottleneck problem and concluded that the problem can be predicted and avoided. The channels are assumed to be orthogonal. The protocol introduces up to six control packets which are exchanged on the control channel before a data channel is reserved. There is a lot of signalling involved causing high overhead costs.

The signalling overhead degrades significantly the capacity and the scheduling capacity of the control channel. The signalling overhead should be reduced to improve the capacity of the control channel. The six control packets result in the worst case of the MSC. Furthermore, the MSC is repetitive and should be reduced to improve the performance of the protocol.

A Distributed Queue Dual Channel (DQDC) scheme is proposed in [61]. The scheme seeks to increase the utilization of data channel and to increase the achieved throughput. The scheme uses one control channel and at least one data channel. The control packets are exchanged by nodes on the control channel which wish to reserve one of the data channels. Data frames and ACK packets are transmitted on the data channels.

Each node maintains a distributed queue (DQ) and updates its reservation DQ regularly to avoid collisions on the data channel. To update the reservation DQ the node relies on the information contained in the overheard control packets. The scheme maintains a distributed queue of all communicating pairs which have reserved the data channels. The DQDC introduces a four way packet handshake negotiation scheme. The following packets are exchanged before a data channel is reserved: Mesh Transmission Opportunity Request (MTXOP REQ), Mesh Transmission Opportunity Response (MTXOP RSP), Mesh Transmission Opportunity Acknowledgment (MTXOP ACK) and Agreement Indicator (AID).

The sender first sends a MTXOP REQ which includes the IDs for the sender and receiver. It also contains the duration and starting time of the transmission. If the receiver rejects the sender's schedule it responds with the MTXOP RSP packet and includes its own preferred transmission schedule indicating its duration and its starting time of the transmission. The sender then sends back the MTXOP ACK packet accepting the receiver's preferred transmission schedule. The MTXOP ACK can be sent by a node to either reject or accept a proposed transmission schedule. The MTXOP ACK is sent in reply to either the MTXOP REQ or the MTXOP RSP. The receiver replies with the AID packet to complete the data channel reservation. The AID is sent by the node which has received a positive MTXOP ACK. It is broadcasted to all the nodes to advertise the transmission agreement reached by the sender and receiver. It marks the conclusion of the negotiation process.

The signalling overhead is too high and it degrades the capacity of the control channel. It also increases the MSC. However, a three way handshake is possible where the receiver accepts the sender's MTXOP REQ. The receiver will send back the MTXOP ACK if it accepts the sender's preferred transmission schedule. Thereafter, the sender will broadcast the AID to advertise the agreement. Though a three way handshake has less impact on the control channel and MSC, it is still too high. There is a need to reduce the signalling overhead in both cases to improve the efficiency of the control channel. One other possible way is to equip the network with intelligence to assist nodes in reserving data channels and to reduce the need for long control channel handshakes.

When the data channel has been reserved, neighbouring nodes are notified through the AID which is sent by the node which has received the MTXOP ACK packet. The AID is a broadcasted packet which fails to reach nodes which are currently transmitting on the data channels and those which are hidden to the AID broadcasting node. As a result, the nodes will have insufficient knowledge of the network status which may lead to data collisions and packet retransmissions. The retransmission of packets will further degrade the protocol.

Nodes returning to the control channel assume that the data channels are busy until they overhear one of the control packets or after the expiry of the set threshold. If the returning node has a data packet to transmit, it has to defer the transmission affecting the quality of service provisioning of time bounded data packets. Furthermore the signalling overhead is significant and it degrades the performance of the protocol. Nodes have to update their DQ each time they receive an AID or the MTXOP ACK packet. The DQ requires a node with unlimited processing power. Unfortunately mobile nodes suffer from low capacity, limited storage, and processing power.

A scheme implementing a separate control channel and N traffic channels is proposed in [5]. The authors attest that the number of channels should be less than the number of terminals for the efficiency of the protocol. A node can transmit and receive on any of the available traffic channels. The RTS/CTS packets are sent on the control channel and a data channel is reserved by the receiver. When the receiver receives an RTS, it selects the clearest channel to be reserved and then sends the CTS packet. Unfortunately, a CTS based data channel reservation scheme fails to calm hidden nodes at the sender's neighbourhood. Data packets will be destroyed by hidden nodes at data reception forcing the protocol to retransmit the affected packets. Retransmissions degrade the performance of the control channel.

A node first senses all the data channels including the control channel before it sends an RTS packet. It then embeds the list of all free data channels in the RTS packet. This means that the RTS's length is increased to accommodate the channel list information to be sent to the receiver. Upon receiving the RTS, the receiving node first senses all the channels and then compares its channel list with the one sent by the sender. The destination node then identifies common free channels and selects the best channel from the list. The destination node then sends the CTS packet to the source node embedding the best data channel. The scheme does not consider channel switching penalty in its timeouts. When the destination node fails to select a data channel, it does not send back the CTS packet. The source node will have to try after the timeout of the CTS packet. This is a good approach which ensures that the control channel is not degraded with reattempts and retransmissions.

Nodes are assumed to be able to carrier sense all the channels simultaneously. However, this is not possible. Nodes can sense one channel at a time and then switch on the next channel before sensing it. This forces a node to incur high overhead costs which relate to sensing and channel switching delays. It is further assumed that a node can receive multiple packets on different channel simultaneously which is not possible with a single transceiver.

The data channels are idle during the contention phase; hence their bandwidth is not utilized effectively. This challenge is common with all the multi-channel MAC protocols and it needs to be addressed to improve the efficiency of multi-channel MAC protocols.

In [3], an asynchronous Multi-Channel Coordination Protocol (AMCP) is proposed. The protocol employs a single transceiver and a dedicated common control channel. Nodes contend for the control channel using the RTS/CTS packets and then reserve the data channels using channel table information. An RTS packet is sent with a list of free data

channels and a preferred data channel. If the preferred data channel is free at the receiver end a confirming CTS packet is sent back to the sender, otherwise a rejecting CTS packet will be sent. Data channels timers are stored in the local channel tables and the respective data channels are reserved when their timers have expired.

When the sender's preferred data channel is rejected by the receiver, the sender has to randomly select the receiver's suggested data channels and restarts the contention cycle. In a worst case scenario the repeated contention cycles may increase exponentially resulting in long signalling delays, degrading significantly the capacity of the control channel.

The protocol may work well when the network is assumed be in operational, unfortunately it may fail when it is implemented in a newly deployed network. All nodes will set all the data channels unavailable and enter into an indefinite cycle waiting passively to overhear control packets. All the nodes will defer their transmission and there will be no control packets that will be overheard on the control channel. As a result, the nodes will fail to update their local channel tables and schedule their next transmissions.

A similar challenge can be faced by joining nodes. A joining node has to first set all the channels unavailable and defer its next transmission until it overhears control packets. It then updates its local channel table before contending for the control channel. Assuming that all the nodes which are on the network have no data to send, the new node will not be able to send its packets until the resident nodes start communicating. In this case the new nodes will be blocked due to the lack of adequate knowledge of the status of the network. Lastly, returning nodes are also expected to defer their next transmissions until they have adequate knowledge of the network, which degrades the performance of the network and affects the quality requirements of the real time and time bounded data.

The challenge of returning nodes, newly deployed networks and of the nodes which join an inactive network can be solved by allowing nodes to sense the data channels before initiating a communication. Unfortunately, sensing all the channels increases substantially the signalling overhead which in turn degrades the capacity of the control channel. The nodes have to sense and switch between channels, which is a heavy penalty to pay. A network supported contention scheme may be a cheaper and effective solution.

The rejecting CTS packet which is sent back to the sender by the AMCP protocol includes a list of data channels which are free, to inform the sender about the available data channels. The sender will select one of the listed data channels in its next attempt. Unfortunately the CTS do not include timers of the unavailable data channels to help a sender which would want to contend for currently unavailable data channel when it becomes free.

It is possible that all the data channels may be busy in the receiver end and this information may be of vital importance if it were included in the rejecting CTS. The free data channels can be reserved by other nodes ahead of a given node does so. Furthermore, successive new contention cycles waste the capacity of the control channel and increase its saturation rate.

It should also be noted that the sizes of both RTS and CTS packets have to be increased to cater for additional required information. The rejecting CTS packet is likely to be a couple of bytes longer than the standard CTS. This means that more bandwidth will be required to transmit the new RTS, the Confirming CTS and the rejecting CTS packets. Given the need for more capacity of the control channel, any further degradation of the control channel should be avoided.

There is a need for local channel tables to be stored and be updated frequently. However, nodes have limited storage and processing power. The ACMP is also affected by the MSC. The multi-channel MAC protocols should endeavour to improve the capacity of the control channel and reduce both the signalling overhead costs and the effects of the MSC.

In [6], a scheme employing busy signals is proposed. The scheme assumes that a transceiver can listen on all the channels simultaneously. A single channel is divided into two sub channels, a control and a data channel. The control channel is used to send the control packets while the data frames are sent on the data channel. While the nodes are sending and receiving data they transmit busy tones on the control channel. During the transmission of data frames, the control is not used for the transmission of the control packets. It transmits busy tone signals. This wastes the capacity of the control channel and reduces its scheduling capacity. The data channels are not used during data channel reservation while the control channel is underutilized during data transmission. The use of the channels should be well coordinated to solve the MSC and to improve the efficiency of the protocol. The scheme assumes that a node can send and listen at the same time. It also assumes that a node can transmit on two channels simultaneously which is not possible.

3.1.5 Channel Hopping Multi-channel MAC protocols

In this Section, a few multi-channel MAC protocols which do not employ the idea of the control channel are analyzed. The protocols implement the channel or frequency hopping concept. The coordination of channels and the synchronization of hopping sequences are of interest. The channel hopping technique, though a good idea; is complex and does not provide a common reference for the terminals to synchronize. This leads to the partitioning of the network and the creation of logical segments in the network.

The Slotted Seeded Channel Hopping (SSCH) [14] is a time based protocol and its performance is affected by a need for global time synchronization. The SSCH suffer from the missing receiver problem and the hidden nodes. If the receiver is deaf, the sending node will be allowed two attempts in one slot. The allocation of two slots to one node wastes bandwidth and causes signalling delays. First In First Out (FIFO) queues are maintained at each node and packets are transmitted in a round robin basis in a given neighbourhood. Each packet which is not transmitted due to problems such as the MRP, has its priority reduced. However, it is not clear how the nodes are grouped into different neighbourhoods. The head of line problem is also a challenge in this scheme. A packet in the head of the queue cannot be removed to make way for the next packet with a higher priority. When a number of packets which are destined to one node are not delivered after the expiry of the slot, they are all dropped after wasting a significant amount of bandwidth and network resources.

A node switches to all the available channels in each schedule. Given the maximum channel switching delay of $224\mu\text{s}$, the switching overhead is too high and heavy. The notion of slotted and cyclical data transmission is good. However, nodes should be limited to very few channels in any given slot to reduce signalling delay. Furthermore, the SSCH requires clock synchronization to ensure that slots of different nodes start and end at the same time. Nodes are expected to send, receive or forward packets during a given slot. This means that technically, there are receiving, sending and forwarding slots and during these slots some data packets should be buffered. For example, if one node is going to be sending its packets in the next slot, all its incoming packets will be buffered. This causes longer transmission delays which should be reduced to improve the performance of the network. The quality of delay sensitive packets is degraded when they are buffered.

The scheme proposed in [62] is a frequency hopping scheme in which radios hop between available channels. It is a polling based scheme which wastes bandwidth when a polled node does not have data to send. It is not robust and flexible. The protocol requires synchronization which is a challenge in mobile networks. Furthermore, the receiver reserves the channel and fails to notify nodes which are in the carrier sensing zone of the sender and those that are hidden from it.

The idea of a common channel is also exploited. Nodes listen on the common channel in an attempt to synchronize their hopping sequences. Carrier sensing is not implemented, and nodes rely on their hopping sequences.

When the nodes begin their hopping sequences, they first enter into PASSIVE state which is equal to the time spent on a hop (dwell time), and then they move into an RTR state on each hop before they transmit data. During the RTR state, an RTR packet is sent to the target destination. The source responds by sending data packets of the polling node in the XMIT state, otherwise sends a CTS packet. When the CTS packet is sent, signalling duration increases. Furthermore, during the RTR state nodes send the RTR packets without sensing the current frequency hop which results in RTR collisions.

W-CHAMB proposed in [63] is a TDMA based scheme which requires global clock synchronization. The protocol implements two in-band energy signals which waste bandwidth. The W-CHAMB implements the idea of prioritized access. The concept has three phases; these are the Prioritization Phase (PP), Contention Phase (CP), and the Transmission Phase (PP). There is a lot of contention that takes place during the PP and the CP which result in high overhead costs. Data frames are assigned priority levels which are used to prioritize the transmission of data packets. However, it is not clear how the scheme solves the head of line (HOL) problem when a packet with the highest priority is blocked by the one with less priority.

The protocol proposed in [64] is called the Multi-channel MAC (McMAC). Nodes hop in a pseudo random fashion, independent of each other. A node is expected to synchronize with its neighbour's hopping sequence. Unfortunately, synchronization is not possible in wireless communications.

To address the synchronization problem, a guard time is implemented by the McMAC protocol to ensure that neighbourhood nodes are synchronized. The idea of the guard time is good; unfortunately, it further degrades the performance of the protocol. The bandwidth used as a guard band can be used for data transmission purposes. Every packet sent includes a 32 bit field which stores current time and seed. However, the time stamp increases the payload of the protocol.

A new node which joins a network has to first wait for ten seconds before it establishes and follows its hopping sequence. On the other hand courtesy HELLO packets are sent to a newly discovered neighbour. The HELLO messages and the ten seconds waiting period do degrade the performance of the proposed protocol.

3.2 Open Research Issues

A handful of open research issues and gaps still exist in the multi-channel MAC protocols which are designed for wireless access networks such as the WMN. For example, to date there is no paper which has attempted to address the MSC. The existing MAC protocols that implement either a dedicated or temporary control channel under utilize the bandwidth of the data channels during the reservation phase. The control channel is not able to schedule successful data transmission to all data channels simultaneously. As a result the bandwidth of the idle data channels is wasted. This problem is recurring and it degrades the performance of MAC protocols.

The MSC can be addressed in twofold. It can either be reduced or limited to the first cycle. When the MSC is limited to the first phase, it is by default eliminated in all the successive phases. Unfortunately, the MSC cannot be eliminated in the first phase. There is a need therefore, to address the MSC for better performance.

A number of multi-channel MAC protocols have either introduced a few new control packets or increased the sizes of the existing control packets. Though the techniques are designed to reduce the channel sensing and channel switching penalty in conjunction with the use of the data structures, they increase significantly the signalling overhead. The signalling overhead degrades the capacity of the control channel and impact negatively on its scheduling capacity.

Design techniques which reduce the control channel signalling overhead should be designed. The main goal of the multi-channel MAC protocol implementing a control channel should be to minimize signalling overhead. The capacity of the control channel should be increased for better performance to be realized.

Multi-channel MAC protocol designers assume that all the channels are orthogonal. Unfortunately, the channels do overlap. If the channel separations were to be increased to ensure that channels are orthogonal, very few non overlapping channels will be created. Implementing a control channel in a system with very few channels does not offer any performance benefits. A number of good MAC protocols which have been designed will not serve their intended purposes if the channels are few. There is a need to closely examine this issue. Possible strategies of increasing the number of non overlapping channels should be

investigated. The use of CDMA should be closely investigated in this regard for its interference averaging and resisting properties. Channel assignment strategies should also be considered and closely investigated as possible solutions.

Lastly, it should be determined through research, the optimum number of channels which can be supported efficiently by a single radio before we entertain any need to use multi radios. Increasing the number of radios without taking into consideration the efficiency, effectiveness and optimality of the multi-channel MAC protocols may prove to be every expensive. The envisioned performance of such multi radio systems may not justify a need for such expensive and complex design approaches. Good design techniques should not be sacrificed for increased end to end throughput which is attained by merely increasing the number of radios. Papers [65] to [76] discuss some of these ideas.

3.3 Summary

The WMN are a promising candidate of the NGWN. However, the limited capacity of the WMN has to be addressed to meet the envisioned NGWN high data rates. The MAC protocol designers are currently researching on strategies that may avail more capacity. One of the active research areas in this regard is the implementation of multi-channel MAC protocols.

The multi-channel MAC protocols which implement a control channel have an edge in the sense that they facilitate network connectivity and provide nodes with a common point of reference. Nodes listen on the control channel and can quickly synchronize on it. The control channel approach needs to be optimized and enhanced. The underutilization of data channels during contention should also be addressed.

The number of available orthogonal channels should be closely investigated. On the other hand new techniques of reducing interference between overlapping channels should be studied. The implementation of CDMA could be one of the possible approaches that can avail more orthogonal channels. Lastly, good coordination and channel scheduling techniques can also be employed to address this problem.

Chapter 4 The Cyclic Scheduling Algorithm

4.0 Introduction

In this chapter, we propose and model the CSA which is designed to address the MSC and the high signalling overhead cost. It also characterizes and models the MSC challenge and shows how it degrades the MAC protocols. The scheme implements an IEEE 802.11 type of MAC protocol. The CSA falls under the Dedicated Control Channel category of multi-channel MAC protocols.

The design of multi-channel MAC protocols in WMN has produced some encouraging results. The multi-channel approach increases network capacity and throughput. However, there are outstanding issues which degrade the capacity of multi-channel systems. The channel assignment, selection and coordination strategies which have been implemented result in the creation of a new multi-channel degradation challenge which we call the Multi-channel Scheduling Cost (MSC). It is a scheduling problem which wastes the capacity of data channels during the data channel reservation phase. As the data channels are reserved in different turns and data transmissions are scheduled, other data channels lie idle. The bandwidth of these data channels is under-utilized when they lie idle, waiting for their turns. Furthermore, the signalling overhead cost is too high and needs to be reduced to improve the performance of multi-channel MAC protocols.

The MSC is repetitive and cyclic. It affects the most the last channels to be reserved even more. In any given cycle, the first data channel to be reserved will be subjected to the least degradation caused by the MSC, while the last data channel will be significantly degraded as it waits for the longest time interval for its turn. The MSC is repetitive in all the cycles during the entire communication process. It is a recurring challenge which has adverse effects on both the control and the data channels. Therefore, there is a need to address the MSC and to improve the performance of the multi-channel MAC protocols.

The MSC manifest itself in multi-channel MAC protocols which implement either a temporary or a dedicated control channel. However, some other approaches do suffer from other variations of the MSC. In this thesis we focus on the multi-channel MAC protocols that employ the idea of a common signalling channel. The signalling overhead is also addressed to improve the scheduling capacity of the control channel. We characterize and show the effects of the MSC on the performance of the network. A proposed solution to MSC is then presented and numerical results are obtained and discussed.

4.1 System Model

The MSC is a new multi-channel challenge which was first identified in this project. In this thesis, a solution to the MSC is proposed. The architectural design of the solution is presented and discussed. We propose a Cyclical Scheduling Algorithm (CSA) which is equipped with a network support infrastructure. The network infrastructure is designed to provide terminals with adequate network information and status which is required for the reservation of the data

channels through the control channel. The CSA reduces the MSC and limits it to the first cycle. It also reduces the signalling overhead cost on the control channel.

The network support infrastructure is designed to reduce the amount of signalling delays to improve both the capacity and scheduling capacity of the control channel. The network support system is designed to also equip returning nodes, joining nodes and nodes in a newly deployed network with adequate network status. It enables such nodes to initiate communication without a need to defer until they have acquired adequate information through the overhead control packets.

We first characterize and model the MSC to put it into perspective. We show how the MSC is a challenge and how it degrades the capacity of data channels including the control channel. The channels are underutilized owing to inability of multi-channel MAC protocols implementing a control channel to schedule simultaneous data transmissions to all the available data channels.

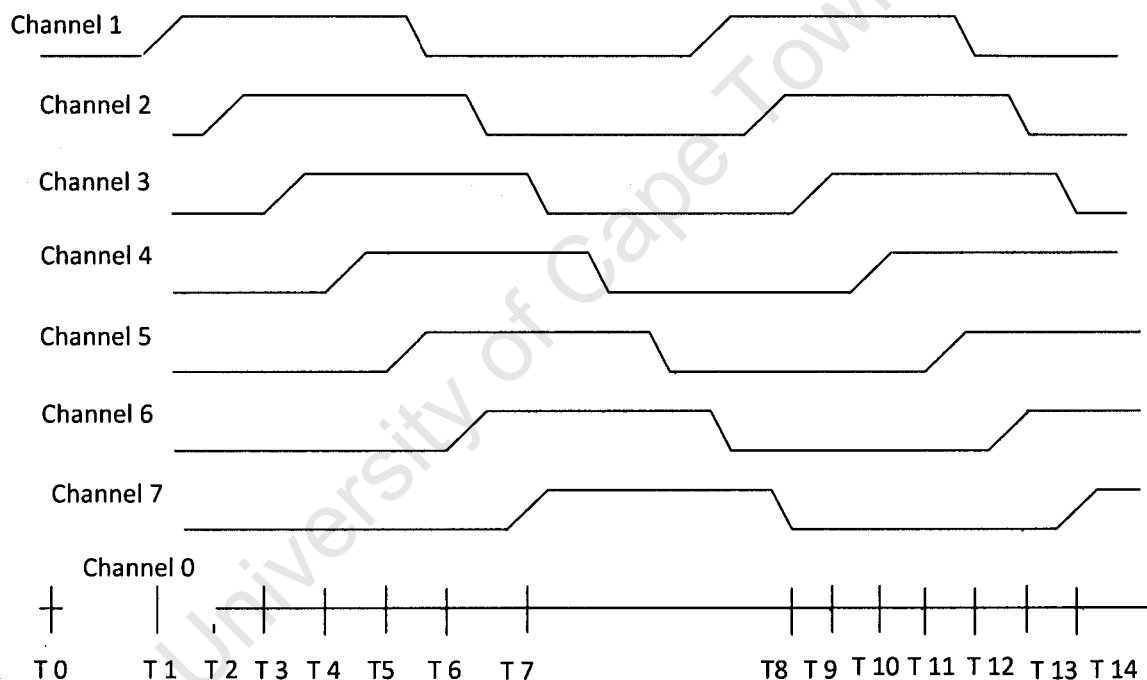


Figure 4. 1. The Multi-Channel Scheduling Cost

Fig 4.1 shows the severity of the MSC. It shows the extent at which control and data channels are underutilized. The vertical axis denotes the number of channels marked channel 0 to 7. The horizontal axis denotes the elapsed transmission time. It is assumed that channel 0 is the control channel and the rest of the channels are data channels. The capacity of all data channels is underutilized between T0 and T1 while nodes are busy contending for the control channel and reserving Channel 1. Channel 2 is reserved between epoch T1 and T2, while all other channels lie idle except channel 1 which is currently transmitting data. In essence, Channel 1 is underutilized between T0 and T1, Channel 2, is being underutilized between T0 and T2, Channel 3 lies idle between T0 and T3, channel 4 between T0 and T4, channel 5 is

idle between T0 and T5, while channel 6 is idle between T0 and T6. Lastly, channel 7 lies idle between T0 and T7.

The last channel to be reserved is subjected to the worst effect of the MSC while the channel which is reserved first suffers the least. On the other hand the control channel lies idle between T7 and T8. Thereafter the pattern is repeated for Data channels from T8 to T14. This shows that the effects of the MSC are repetitive and recurring. The MSC degrades severely the performance of the multichannel MAC protocols as illustrated in Fig 4.1. The illustration clearly demonstrates the significance of this project and the magnitude of the MSC challenge. The proposed model restricts the MSC to the first cycle, there after its effects are eliminated. It is not possible to eliminate the MSC in the first cycle. Data transmissions cannot be scheduled to all the available data channels concurrently.

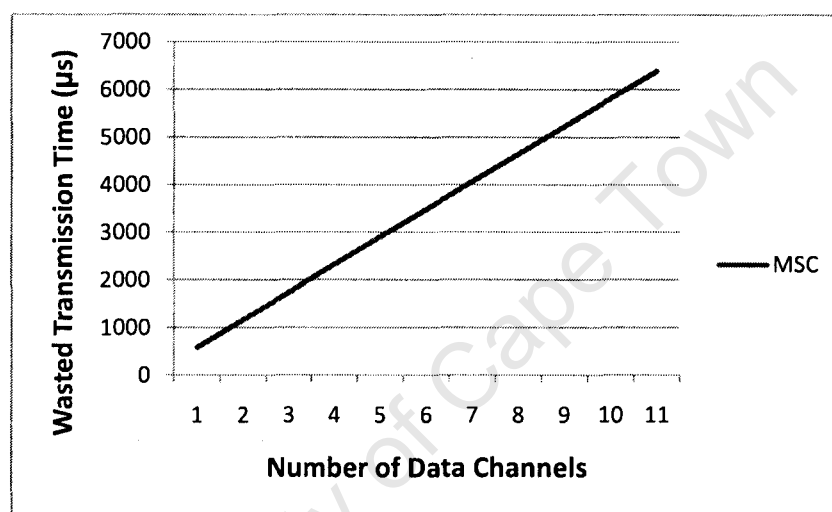


Figure 4. 2. The Behaviour of the MSC as the number of data channels are increased

Fig 4.2 shows that the behaviour of the MSC increases with the increase in the number of data channels. It shows how the MSC relates to the number of data channels employed in the system. The second data channel incurs twice the degradation of the first data channel, while the degradation of the third data channel is twice that of the first data channel. The degradation of the fourth data channel is four times that of the first data channel. Thus, the MSC effects increase in this manner until the last data channel is reached. The total wasted bandwidth is the summation of wasted bandwidth on each data channel implemented in the system. This is a high cost which requires an effective and efficient solution. It degrades severely the performance of multi channel MAC protocols.

4.2 Protocol Descriptions

The scheme requires the implementation of the network support infrastructure which avails the network information to nodes to expedite data channel reservation. The signalling overhead cost is therefore reduced and the MSC addressed. The structure is therefore presented and described before the proposed model is presented.

The network support infrastructure is made up of a network of mesh routers incorporated in the ad hoc network of mesh clients. Each mesh client is within the communication range of one of the network mesh routers. The network mesh routers are powerful, intelligent and have a wider communication range. Their communication ranges are longer to reach as many mesh clients as possible. Each mesh router of the network support infrastructure is within the communication range of the next network mesh router of the network support systems. The network support system is also designed to provide joining and returning nodes with necessary information which enables them to initiate their next transmission immediately instead of deferring them to a later stage. It takes advantage of the composition of the WMN and its different nodes which have different capabilities.

A hybrid WMN that incorporates a backbone of fully connected mesh routers within the ad hoc network of mesh clients is proposed. The proposed network support infrastructure is illustrated in Fig 4.3. It consists of routers enclosed by blue lines. It is a network of mesh routers which is deployed within the ad hoc network of mobile clients. The routers are within range of each other and provide a full coverage of the ad hoc network of mobile mesh routers. The mobile nodes which are not within the coverage of the network support are outside the scope of this project. However, they can overhear packets of mesh clients within their proximity though they may be subjected to some delays.



Figure 4. 3. The architecture of the proposed network support infrastructure in a hybrid mesh network

Each mesh router which is part of the network support maintains a data structure called a Network Status Table (NST). These mesh routers are referred to as the NST nodes. The NST nodes store information about the availability of data channels, list of data channels which are in use and when they would be available. A data channel will be said to be available when its remaining transmission time is equal to the amount of time required for the next pair to reserve it. The remaining time is determined by the inter-cycle time technique discussed earlier. The inter-cycle duration is stored in the NST as the data transmission duration of a given data channel. The network support nodes also maintain a sequence of data channels to ensure that data transmission is scheduled in a round robin bases. The information maintained in the status tables is made available to any node which probes the NST node for network status.

Data transmission on data channels is scheduled in cycles, when each data channel is about to be free to improve the scheduling capacity of the control channel and eliminate the effects of the MSC. The sending nodes will start contending for the control channel when the busy data channel is about to be free. A data channel is said to be free when its remaining transmission time is equal to the control channel handshake. Once this condition is met, the next pair starts reserving the current data channel. When a control channel is won, the data channel which is going to be free next is reserved.

The transmission cycles are determined by the number of data channels which are implemented. In each cycle, all data channels have a single opportunity to transmit data. When all data channels have transmitted data once, the current transmission cycle expires and the next cycle begins. Data transmission on data channels is scheduled in a round robin basis. This gives all the data channels a single chance to transmit data in each cycle. Furthermore, it is assumed that user transmission sessions are of equal length and constant.

The reservation and the handshake of control packets will be done before the data channel to be reserved becomes free. Data channel reservation starts when the remaining transmission time of the current transmission on the data channel is exactly equal to the duration of the control channel handshake. The data channel will only become free as the new pair is switching onto the reserved data channel. The switching will be completed when the data channel is free. To ensure that the timing is perfect, an inter-cycle duration which depends on the number of data channels is designed.

The inter-cycle time technique is computed using equation 4.1. The variable *Intcyc* is the inter-cycle time. The D_f is the transmission duration of the data frames, sw is the multi-channel switching time, DC_n is the number of data channels and hd is the total transmission of the control packets on the control channel. The ACK packet is not part of the hd since it is transmitted on the data channels. For example, in a network with three data channels, the inter-cycle time will be equal to the total transmission duration of a data packet plus one channel switching duration less the summation of three control channel handshake durations. The inter-cycle duration reduces as more data channels are implemented.

$$Intcyc = D_f + 2 * sw - DC_n * hd - sw \quad (4.1)$$

The pair which wins the control channel in phase one will access the first data channel and in the N^{th} phase the N^{th} data channel will be reserved by the N^{th} pair. The cyclic scheduling algorithm will be memory based (network support) keeping track of all the activities on data channels, cycles and phases within cycles. These details will be stored on the network support infrastructure of multitasking mesh routers in a hybrid Mesh network.

When a node wishes to send data and does not have a complete understanding of the network status, it probes first the nearest NST node. Upon receiving necessary information it will be able to exchange the control packets (RTS/CTS) on the control channel and reserve a data channel which will be available next. The reservation is done before the data channel becomes idle after the inter-cycle duration.

The network support system is of paramount importance for a network which has just been deployed. In such a scenario nodes would not have a complete picture of the network status. Instead of waiting indefinitely in attempt to gather information from overheard control packets, node will simply probe the nearest NST node. All the nodes current on the control channel and which are within the reach of the NST node will receive the responses to the probes. The responses will be used by a number of nodes to update their own local tables. The local tables are expected to be small and limited in size. This will help nodes with limited processing power to store and update their local tables effectively.

The NST information will also be helpful to joining and returning nodes. A node which has just been registered is considered to be a joining node. A joining node could be a node which has moved from one NST node zone into the zone of the next NST node. Nodes can also be referred to as joining nodes when they have been handed over to the next network. On the other hand, a node is said to be returning if it was busy transmitting or receiving on a data channel. Upon the completion of their transmission, a node switches back onto the control channel. These nodes would have missed the details of data channels which were reserved during their absence. When the returning nodes wish to initiate communication immediately upon their return, they must first send a probe to the nearest NST node otherwise they will not communicate due to lack of sufficient network information. The network support system therefore, prevents the deferment of transmission and reduces bandwidth wastage due to false blocking of nodes with insufficient information.

Fig 4.4 shows the implementation of the network support infrastructure in the cyclic scheduling algorithm. If the network is available, a given node can contend for the access of the control channel, otherwise it has to first probe the nearest NST node for detailed status of the network.

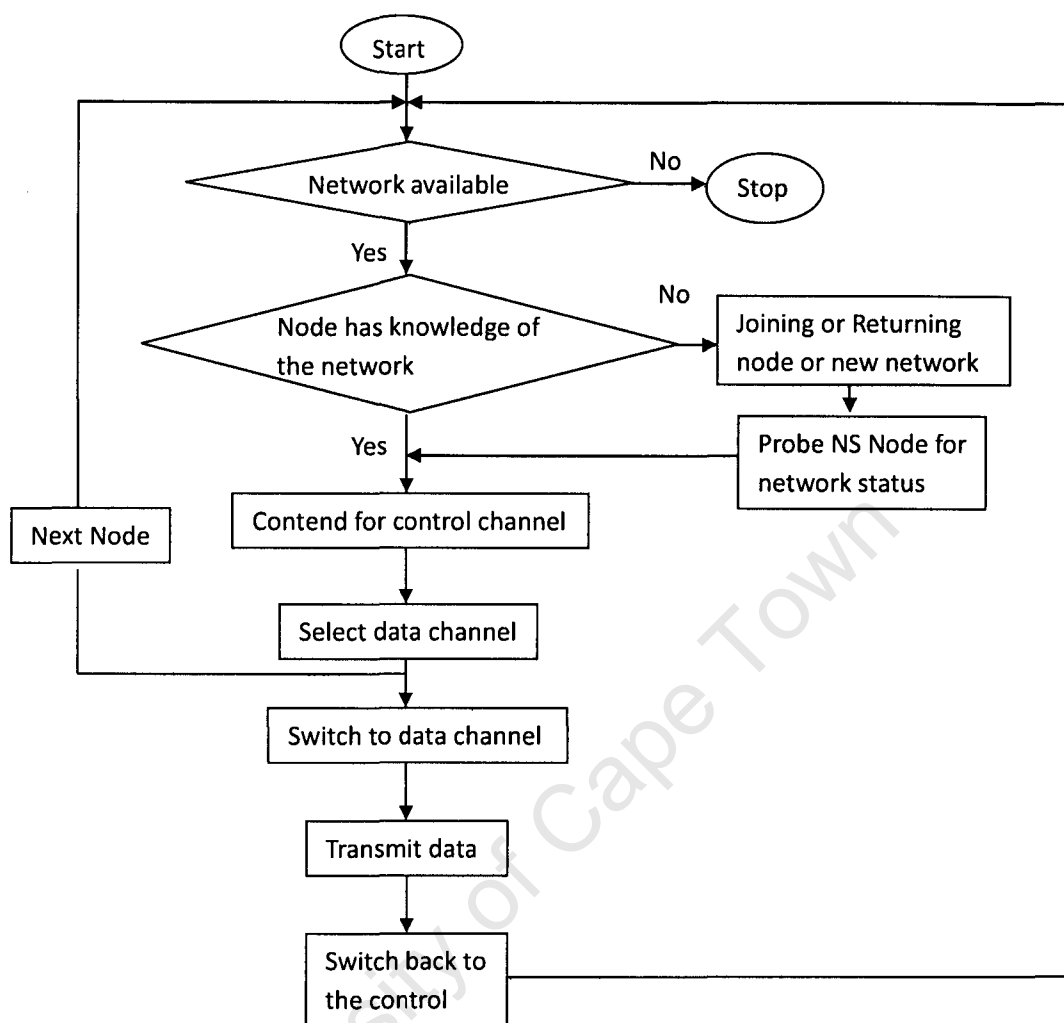


Figure 4. 4. The implementation of the network infrastructure in the Cyclic Scheduling Algorithm

There are three types of nodes which may not have the complete picture of the network. These are the joining nodes, the returning or the start-up nodes. A node which has been transmitting on a data channel will have insufficient knowledge of the network upon its return to the control channel. This also applies to a node which has just joined the network. Lastly, if the network has just been deployed, all the nodes will have insufficient knowledge of the network and will require the services of the network support system. Once the probe responses have been received, a node can contend for the access of the control channel. The probing technique is used mostly by returning nodes; hence the probing frequency is low. The probing technique eliminates the need for a waiting period and it also reduces the MSC.

A mesh client with insufficient network information will be able to contend for the control channel and select an available data channel after receiving the probe. All the required information will be sent to the probing node by the NST node. Overhearing nodes will also update their own tables if they need to do so. The network support of the overlaid mesh

routers will store information about the status of data channels. It will contain information on free channels, and the list of data channels which are going to be free soon and their respective remaining times. This information will be sent to nodes upon request to help them decide when to contend for the next data channel.

The network support approach ensures that a network does not enter into an infinite loop, a deadly embrace, where a node waits indefinitely to hear a sent control packet. However, in our approach this state is addressed by the network support of mesh routers. The network mesh routers have correct information on the status of the network. They equip returning and joining nodes with up to date status of the network through probe responses. The network support system will also equip nodes in a newly deployed network with the required network status to facilitate their communication.

4.3 The Control Inter-Frame Space

Multi-channel MAC protocols implement the IEEE 802.11 family of standard which is a de facto standard for single channel MAC protocols. The standard implements the Extended Inter-Frame (EIFS) technique in attempt to address the problems of hidden nodes. Nodes which receive erroneous packets defer for EIFS duration. Unfortunately, this duration is still implemented in multi channel MAC protocols. The EIFS technique is not relevant in multi channel MAC protocols and its implementation worsens the impact of the MSC.

In the implementation of our proposed CSA, the EIFS has been reconfigured and changed into a shorter Inter-Frame Space called the Control IFS (CIFS). The CIFS is the summation of a CTS and a Short IFS (SIFS) durations. When a node receives an erroneous RTS packet, it defers for CIFS. If the received erroneous packet is a CTS, the overhearing nodes do not have to defer their next transmission. If they initiate a communication soon after the erroneous CTS packets, they will not interfere with any node on the control channel.

The nodes have to be able to differentiate between an erroneous RTS and CTS packet for the implementation of the CIFS technique. The detection rules are discussed in details in [77] and [78]. The CIFS ensures that nodes do not defer for too long. The shorter deferring period help reduce the effects of the MSC and it also does reduce the idle durations of the control channel. It improves the capacity of the control channel.

4.4 The Switching Technique

The channel switching technique recognizes the fact that if nodes defer for a summation of one channel switching time and one SIFS, when a data channel has been reserved the control channel would be degraded. When the nodes defer for one channel switching time and one SIFS time, it means the control channel will not be available for a longer duration. However, if this control channel timeout is reduced, the capacity of the control channel would increase. The proposed switching technique addresses the control channel timeout by shortening its length. When the data channel has been reserved, nodes switch onto it immediately without having to defer reducing the length of the control channel timeout. The proposed deferring rules avails the control channel to the next pair sooner.

In our approach, we reconfigure the channel switching time and then re-associate all the switching related costs with data channels. We therefore de-associate channel switching time

from the control channel. We consider the channel switching delay to be $224\mu\text{s}$ as specified in [46]. When two switching penalties are considered the total switching delay amounts to $448\mu\text{s}$. This means that data channels in our scheme will suffer a total delay of $448\mu\text{s}$. In essence we add $448\mu\text{s}$ to the data transmission duration.

The control channel in our scheme is the driver and scheduler of data transmission and data channels. Its capacity affects the performance of the network. The capacity of the control channel should be improved. In the proposed scheme, it is improved by adding the second switching time to the duration of data transmission instead of adding it to the control channel handshake duration. This reduces the idleness of the control channel and improves its capacity and its scheduling capacity. As a result, the control channel can drive many more data channels. It also reduces its saturation rate.

4.5 Model Analysis

The MSC wastes bandwidth on all the data channels and it is repetitive. However, our approach limits the effects of the MSC to the first cycle. This is achieved through the implementation of three techniques discussed in the sequel. The data channels are reserved when they are still busy transmitting their current data frames. This is done through the implementation of the inter-cycle time discussed above. Secondly, the EIFS has been reconfigured and changed into CIFS. In multi-channel MAC protocols, there is no need for nodes which receives erroneous packets to defer for the EIFS duration. If they do so, they worsen the effects of the MSC. The EIFS was designed to protect the ACK packets in single channel MAC protocols. In multi-channel MAC protocols, ACK packets are transmitted on the data channels. Therefore, the EIFS is not relevant.

Thirdly, in the CSA nodes do not defer for SIFS and channel switching delay after data channel reservation. As the node switch onto the reserved data channel, the next pair is allowed to reserve the next available data channel. This approach reduces the waiting period of nodes and also inhibits the MSC. The three approaches reduce the idle periods of the control channel and eliminate all the subsequent idle periods of all the data channels. As a result the effects of the MSC are limited to the first cycle.

The inter-cycle scheme marks the beginning and the end of a given cycle. It defines the minimum duration a data channel will be busy before it is available for the next data transmission in the next cycle. It forces all the terminals intending to use a given data channel to hold back their next transmissions long enough to allow data packets to be delivered successfully. In essence the inter-cycle time starts when the last control packet has been received in the previous cycle and ends when the first control packet is sent in the next cycle.

The inter-cycle duration is not fixed it varies with the number of data channels which have been implemented. It is inversely related to the number of data channels. It has the longest duration when there are only two data channels and its length decreases as more data channels are added.

RTS/CTS	Inter-Cycle								RTS/CTS
RTS/CTS	RTS/CTS	Inter-Cycle						RTS/CTS	RTS/CTS
RTS/CTS	RTS/CTS	RTS/CTS	Inter-Cycle				RTS/CTS	RTS/CTS	RTS/CTS
RTS/CTS	RTS/CTS	RTS/CTS	RTS/CTS	Inter-Cycle		RTS/CTS	RTS/CTS	RTS/CTS	RTS/CTS
RTS/CTS	RTS/CTS	RTS/CTS	RTS/CTS	RTS/CTS	RTS/CTS	RTS/CTS	RTS/CTS	RTS/CTS	RTS/CTS

Figure 4. 5. The Inter-Cycle Scheme

Fig 4.5 shows the behaviour of the inter-cycle duration as the number of data channels is increased. The inter-cycle duration decreases with the number of data channels. As it shrinks, the control channel becomes busier and its capacity improves. Its scheduling capacity also improves to drive many data channels.

The top row depicts a situation where there are two data channels. The control channel will lie idle after performing the handshake of the two data channels until the transmission has ended. Then the handshake will be performed for the next cycle. The duration of the inter-cycle will reduce in the next row when two more data channels have been added. This behaviour will be exhibited by the inter-cycle scheme as more data channels are added. The inter-cycle time reduces the idleness of the control channel and allows data channels to be reserved for the next cycle before they become idle. Fig 5b below clearly shows the benefits of the inter-cycle time and the proposed channel switching techniques in addressing the MSC.

Idle		Data	Idle	
	Switching		Switching	
Control	Idle			Control

(a)

Idle		Data	Idle	Data	Idle
	Switch		Switching		Switching
Control	Inter-Cycle	Control	Inter-Cycle	Control	Inter-Cycle

(b)

Figure 4. 6. The Inter-cycle model which inhibits the effects of the MSC

In Fig 4.6a, we model an approach where the next transmitter awaits for the current transmitting pairs to switch back to the control channel before it contends for the control channel. This approach wastes the capacity of both the control and the data channels. It

increases the effects of the MSC. The channels are idle for long durations. As can be seen in Fig 4.6b, the implementation of the inter-cycle duration has reduced the idle duration of both the control and data channels. The top block in both 4.6a and 4.6b represent the data channel. The bottom block represents the control channel.

In our proposal, the data channel is reserved when it is about to finish the current transmission. As the current communicating pair switch back onto the control channel, the next pair is switching onto the data channel. These terminals will cross each other mid way through their channel switching durations. This enables the control channel to be more capable and to be able to support more data channels which in essence increases its scheduling capacity and reduces the idleness of the channels and addresses the effects of the MSC.

The implementation of the network support infrastructure limits channel contention to the control channel. Two terminals intending to exchange data packets will contend and reserve the control channel with the aid of the network support system when a given data channel is known to be free. Thereafter, they won't be expected to exchange packets to negotiate which data channel to reserve. The reservation of the data channel will be linked to the reservation of the control channel. This will be possible in our CSA framework given the fact that data transmission is done in phases and in cycles. Furthermore, the local node tables and the implementation of the network support infrastructure will provide the required intelligence which will guide the reservation of data channels. The control channel will be reserved during timeslots in which a given data channel is known to be idle. The main goal of this scheme is to reduce the contention and channel reservation time to avail more bandwidth for network performance improvement.

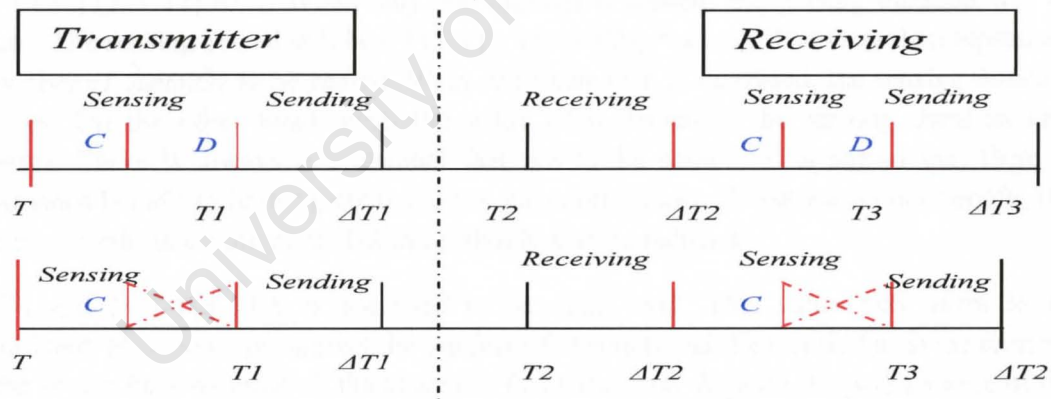


Figure 4. 7. The channel reservation and access scheme

The network support system ensures that a minimum number of control packets are exchanged. It reduces the signalling overhead costs which were highlighted in chapter three of this project. The sizes of control packets are not increased. There are also no additional control packets which have been added. Lastly, nodes do not sense all the data all the channels. They sense only the control channel.

In Fig 4.7, the transmitter has to sense and identify first all the idle data channels during the time interval T to $T1$ and then it sends the list of the free data channels to the receiver at $T1$. The sending node specifies its preferred data channel. The receiver will also upon receiving the RTS packet at time $T2$, check whether the sender's preferred data channel is also free at its end. It may sense other data channels in the list if the preferred data channel is sensed busy. Thereafter, it will send either the confirming or the rejecting CTS back to the transmitter. If the rejecting CTS is sent, the process is repeated. In this generic scheme all the channels are sensed twice, once each communicating pair. The generic scheme is depicted by the top block.

The bottom block depicts our proposed approach where data channels are not sensed by both the receiver and the sender. The sender and the receiver only sense the control channel during timeslots when a given data channel is known to be idle. The terminals use both the physical and the virtual carrier sensing techniques to sense the control channel. Data channels are sensed through the virtual carrier sensing mechanism with the aid of the network support approach we are proposing to implement to improve the intelligence of the network. The network support ensures that all terminals have sufficient knowledge of when the data channels will be available. The implementation of the network support system distinguishes our protocols from the related work. It also ensures our protocols functions well in all cases and possibilities. It does cater for the joining, returning and nodes in a newly deployed network.

Assuming that there are two channels, a control and a data channel, sensing duration will be $(T1 - T) + (T3 - T2)$ long. When only one channel is sensed, the sensing duration will be reduced. The sensing period will be $((T1 - T) + (T3 - T2)) * n$ long. The variable n represents the number of channels to be sensed. When the value of n is increased, the sensing duration increases. On the other hand when the value of n decreases the sensing duration also decreases. There is always one channel that has to be sensed. This shows that there is performance benefit in limiting contention to the control channel. For maximum benefit, the signalling overhead on the control channel should also be reduced.

In [79] and [46] the PCS is specified to be $15\mu s$ long. This value may seem to be insignificant. However, considering the number of channels and the fact that both the receiver and the sender have to sense all the channels, this value may degrade the performance of the network significantly in a network with many channels. For example the sensing duration (d) can be expressed as follows:

$$d = 2 * n * (T1 - T) \quad (4.2)$$

The variable n denotes the number of channels to be sensed twice both by the sender and the receiver. If we have 13 channels and $T1 - T$ is equal to $15\mu s$, the sensing duration will be $390\mu s$. The sensing duration will therefore increase relatively to the number of channels implemented in the network. Setting $T1 - T$ to $15\mu s$ we get;

$$d = 2 * 15\mu s * (n) \quad (4.3)$$

When we limit the PCS to the control channel we reduce the sensing duration by a factor of 15. The sensing duration is expected to be $30\mu\text{s}$ long in our scheme, $15\mu\text{s}$ for the sending terminal and $15\mu\text{s}$ for the receiving terminal. A number of multi-channel MAC protocols are designed to reduce this sensing cost unfortunately at a high signalling cost. We reduce the signalling cost through the implementation of the network support system.

4.6 The effectiveness of the CSA

The cyclic scheduling algorithm will be memory based (network support) keeping track of all the activity on data channels, cycles and phases within cycles. These details will be stored on the network support infrastructure of multitasking mesh routers in a hybrid Mesh network. The pair which wins the control channel in phase one will access the first data channel and in the N^{th} phase the N^{th} data channel will be reserved by the N^{th} pair.

Fig. 4.8 is used to explain the concept behind the cyclic scheduling algorithm. The diagram though not in scale is based on the length of control packets, channel switching duration of $224\mu\text{s}$ and the length of data packets as stipulated in the standard. The durations however, were changed to make them more manageable and easy to work with. For example, short durations were scaled up while longer durations were scaled down. The manipulation of these durations reduces the duration of the inter-cycle hold off time. However, the concept can still be perceived and comprehended.

Channel 0 denotes the control channel, while channels 1 and 2 are the two data channels. The red arrow depicts the channel switching delay. The blue arrows represent data and control packets durations.

In Fig. 4.8 the two communicating pairs (ij) and (xy) will automatically reserve data channels one and two respectively during the first cycle. After the first cycle terminals will back off for the inter-cycle duration to accommodate the switching delay and to properly mark the beginning of the next cycle.

In the next cycle, the next pairs (st) and (uv) will reserve the two data channels while the previous two pairs are still communicating on the same two data channels. As the next pairs are switching to data channels, the first pairs will complete their transmission and start switching back to the control channel to wait for the next cycle if they still have data to send. The switching process is started at the same time by both sets of pairs. The first pair in each cycle must reserve the first data channel. This rule ensures a collision free data exchange on data channels. However, the implementation of the network support system addresses this challenge.

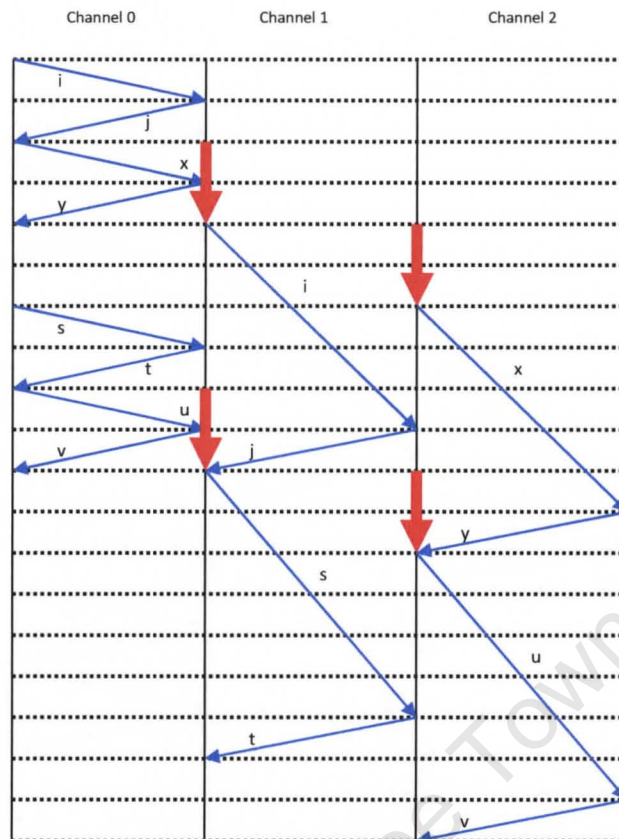


Figure 4. 8. Packet switching analytical diagram

The design of the hold off duration and the channel coordination scheme is fundamental to the success of this scheme. In Fig 4.8 only channel switching delay to a data channel is depicted. The reverse channel switching delay is not shown in the diagram. It can also be seen in the same figure that the effects of the MSC have been limited to the first cycle. In the subsequent cycles, the MSC has been eliminated through the implementation of the inter-cycle time. The bandwidth of both channel 1 and 2 is wasted in the first cycle when pairs (ij) and (xy) exchange control packets on the control channel 0. In the subsequent cycles the effects of the MSC have been eliminated.

The performance of the CSA and its ability to limit the effects of the MSC to the first cycle can be contrasted to the performance of the existing multi channel MAC protocols shown in Fig 4.9. In the existing multi channel MAC protocols the effect of the MSC is recurring and is repetitive in each and every cycle. In both Figs 4.9 and 4.8, bandwidth is wasted in the first cycle as (ij) and (xy) are busy reserving the two data channels. However, in Fig 4.9 more bandwidth is wasted in the successive cycles. For example, the two data channels are idle when (st), (uv) and then later (ij) are busy on the control channel reserving the data channels. The implementation of the CSA scheme has managed to eliminate these successive costs and limit the effects of the MSC to the first cycle. The CSA scheme is effective in solving the effects of the MSC. The effects of the MSC cannot be eliminated in the first cycle.

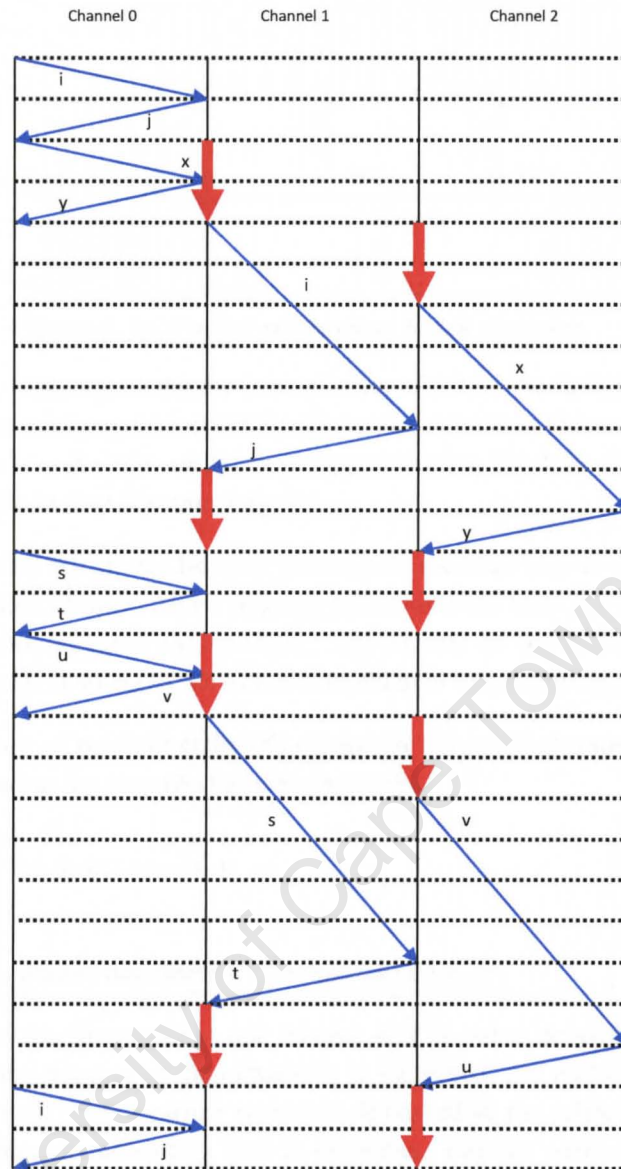


Figure 4. 9. The effect of the MSC on multi channel MAC protocols.

In Fig 4.10, we present RTS, CTS, DATA and ACK packets handshake in a block diagram. It can be seen that this approach waste bandwidth on the data channels during the first cycle. This is caused by the switching delay and the use of multiple channels. This bandwidth wastage is referred to as the multi-channel scheduling cost. In the related work, the CSA is recurring and repetitive. Our proposed scheme eliminates the effects of the MSC in the subsequent cycles and limits its effects to the first cycle as shown in both Figs 4.8 and 4.10. In the existing protocols, this cost is periodic as shown in related work. The switching cost and the multi-channel scheduling cost are not evident in the subsequent phases as our cyclic scheduling protocol takes advantage of switching penalty coupled with the inter-cycle time to schedule concurrent transmissions in a proactive manner.

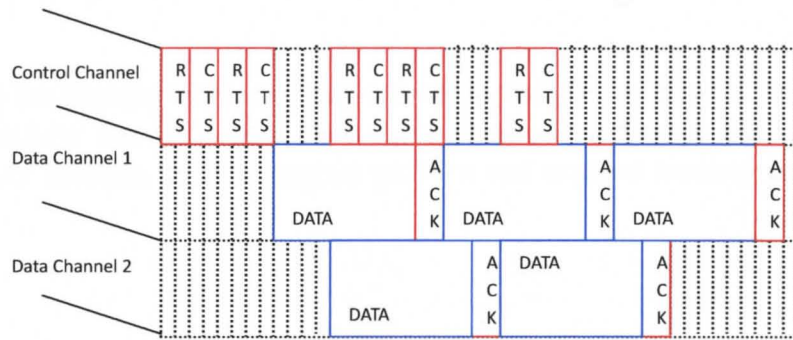


Figure 4.10. Packet scheduling block diagram.

The top block in Fig 4.10, represents the control channel while the last two depicts two data channels. As the nodes exchange the control packets on the control channel, the bandwidth of the two data channels is underutilized. It can be appreciated in Fig 4.10, that the effects of the MSC are not noticeable in the subsequent cycles.

We also present a model which can be used to compute the total cost of the MSC. The MSC affects the most the data channel which is going to be reserved last. The data channel which is reserved first is least affected by the MSC. The effects of the MSC increase with the number of data channels. It worsens with each data channel in each cycle.

To calculate the amount of wasted bandwidth caused by the multi-channel scheduling cost in our scheme, the following for loop can be implemented:

```

for (i = 0; i <= n; i++)
    x += i;
Wasted bandwidth = x * handshake duration;

```

This cost is limited to the first cycle in our scheme and its value depends on the number of data channels N . As the number of data channels is increased, the multi-channel scheduling cost will increase as well. In the earlier protocols discussed in the related work Section, the effect of the multi-channel scheduling cost is repetitive. For the earlier schemes, the total multi channel scheduling cost can be obtained by multiplying the cost of the first cycle by the total number of cycles.

4.7 Summary

The paper proposed a cyclical scheduling algorithm which incorporates channel switching delay in channel scheduling and coordination. It consists of the inter-cycle time technique, the CIFS and the channel switching technique. The proposed scheme is optimised for the new multi-channel interference problem referred to as the multi-channel scheduling cost. It is also designed to reduce the control channel signalling overhead cost.

The analysis shows that the multi-channel scheduling cost can be limited to the first cycle when the cyclical scheduling algorithm is implemented. In the subsequent cycles it can be eliminated by varying the size of the inter-cycle duration and allowing data channels to be

reserved when the ongoing transmissions are about to end. The proposed CSA protocol also provides a platform through which other multi channel interference challenges such as missing receiver problem, hidden terminal problem and exposed terminal problem can be addressed.

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Chapter 5 Analysis of Cyclic Scheduling Algorithm

5.0 Introduction

In this chapter, an efficient multi-channel MAC protocol is proposed. This project proposes an efficient multi-channel MAC scheme which uses the existing control packets to improve the efficiency of the control packet. The protocol reduces the amount of overheard cost on the control channel and improves the utilization of all the available channels. In this chapter, the proposed scheme is evaluated and compared with other related schemes. The analysis shows the efficiency of the proposed scheme and its supremacy over other related schemes.

The proposed scheme, the Cyclical Scheduling Algorithm, is modelled using Queuing Network techniques and Markov Chains. It is modelled as a multiple server system with multiple input and output queues. The control channel is regarded as the driver of the CSA scheme. Therefore, the analysis focuses on the design of the control channel. Its design has a bearing on the performance of multi-channel MAC protocols which implement a dedicated control channel. The control channel is modelled as a single server connected to multiple input queues and multiple output queues. The model clearly shows the significance of reducing the signalling overhead cost on the control channel and the need to improve the utilization of both the control and the data channels. The proposed scheme improves the service rates of the control channel which in turn improves the efficiency and performance of the multi-channel MAC protocols.

The scheme CSA is modelled as an M/M/N system. The first M stands for Markov or Memory less arrival rates, whose inter arrival times are exponentially distributed. The second M stands for Markov or Memory less service times, meaning that the service times are exponential distribution. Lastly, the N denotes the number of servers. The system has three levels of servers; the nodes, the control channel and the data channels. The nodes and the control channel are modelled as an M/M/1 system while the data channels are modelled as the M/M/N system.

Fig 5.1 depicts a number of nodes which are denoted by μ_1 to μ_4 . The nodes are considered to be servers whose output is fed onto the control channel. The control channel is a single server marked μ_5 . The control channel connects to multiple output queues marked as μ_6 to μ_9 . As shown in this model, the design of the control channel is fundamental to improving the performance of the multi-channel MAC protocols.

The packets are generated and arrive at the MAC layer of the communicating nodes with exponential inter arrival times. The service times of the nodes which are required to process the arriving packets are also distributed exponentially with parameter λ_i , $\forall i \in \{1, 2, \dots, N\}$. As a result an M/M/1 system is formed. The inter arrival times of packets at the control channel from different nodes are also distributed exponentially, assuming that packet losses are negligible. The service time of the control channel is distributed exponentially, which result in an M/M/1 system. The distribution of inter arrivals of packets at a number of data channels follows an exponential distribution and the service times of the data channels are distributed

exponentially. The resultant system is an M/M/N. However, the focus of the project is on the control channel and the capacity utilization of the channels.

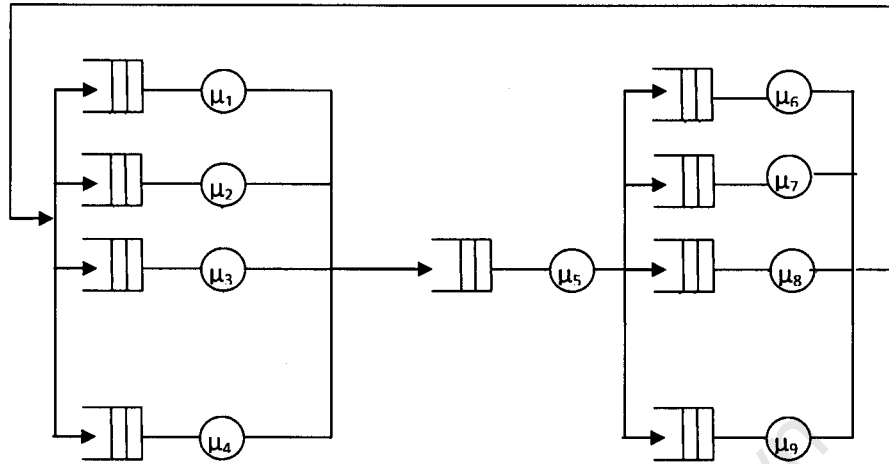


Figure 5. 1. The modelling of multi-channel MAC protocols as multiple servers

The proposed CSA scheme can be described as a memory less system with exponential inter-arrival and service times. It has Markov arrival times and Markov service times. Each server can be modelled as an M/M/1 server. The servers are networked into a series of connected M/M/1 servers. To model the flow of input and output of one server into the next server, the Little's Law is assumed. The Little's Law states that the departure rate of one system or server becomes the arrival rate of the next [80]. The system is seen as a black box with an input rate as its input and an output rate as its output. The concept is represented with the following equation:

$$L = \lambda W \quad (5.1)$$

L denotes the average number of packets in the system; W the average time spent by a packet in the system and λ is the input rate or the arrival rate.

Quantity L can be expressed in terms of the utilization factor or the traffic intensity of system load, Eqn (5.2). The equation gives us the mean number of packets in the system. This is a general property of all queuing systems.

$$L = \sum_{n=0}^{\infty} n \pi_n = \frac{\rho}{1-\rho} \quad (5.2)$$

Fig 5.2 is a classic example depicting the properties and attributes of all the queuing networks. It shows how a typical queuing network system should behave. We therefore, expect our models to behave more or less like the depicted behaviour of a typical queuing network in Fig 5.2. The typical model depicts the general mean number of packets in a system. Equation (5.1) can be implemented to generate the typical behaviour of all the queuing networks.

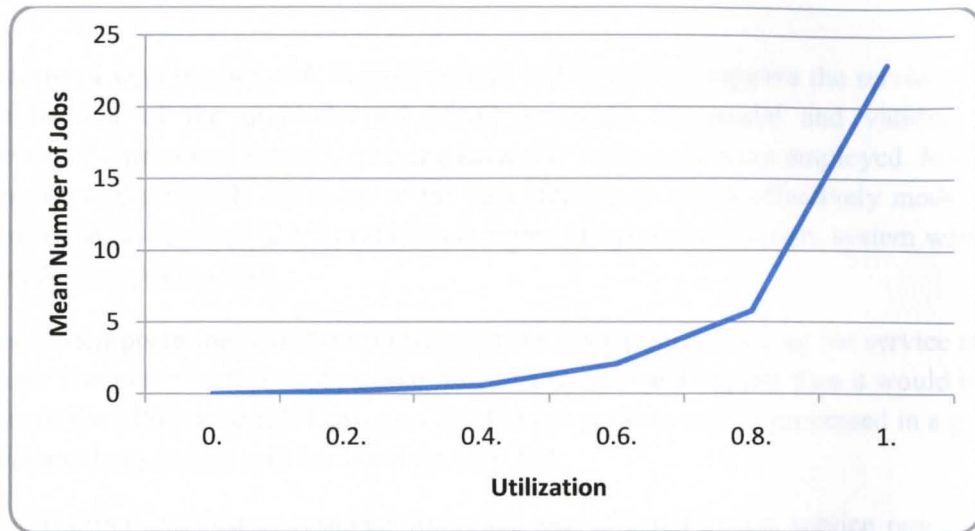


Figure 5.2. The mean number of packets [80]

As can be seen in Fig 5.2, the mean number of packets in the system approaches infinity as the load or traffic intensity ρ approaches the system capacity. This means that as the load approaches the system capacity, the queues become very long. This can be seen in the above diagram as the utilization approaches one.

We can now express the value of ρ and limit it to 1. The quantity ρ is the ratio of the arrival rate to the service rate expressed as:

$$\rho = \lambda / \mu < 1 \quad (5.3)$$

The value of ρ is determined by the service rate μ . If the service rate is low, in Eqn (5.2) the load approaches 1 at a faster rate and the queues start building up very fast. If the service rates are high, the queues build up slowly. This means that in Eqn (5.3), when we divide the arrival rate with a small service rate we get a large value which causes the fast building of the queues in Eqn (5.2) to build up very fast. On the other hand, when we divide the service rates in Eqn (5.3) with a high service rates, a small figure is obtained which in turn delays the building up of long queues in Eqn (5.2).

The relationship between the traffic intensity and the service rate clearly shows the significance of the quantity μ . The variable μ is critical to the performance of the multi-channel MAC protocols. Its value in turn affects the capacity and the scheduling capacity of the control channel. Our proposed scheme is informed by the significance of the service rate to the performance and efficiency of the system. We later also show the significance of the design of the control channel to the performance of multi-channel MAC protocols.

The MSC and the signalling overhead cost have a bearing on the value of the service rate. They degrade the multi-channel MAC protocols by increasing their service times. Poor service times worsen the utilization of the protocols. The service times and the utilization of the multi-channel MAC protocols should be improved for better performance. The CSA

which is equipped with the network support system is designed to improve the service times and the utilization of the multi-channel MAC protocols. To model and validate the effectiveness of the proposed scheme, queuing networks techniques were employed. Markov and queuing networks models are some of the two techniques which effectively model the effectiveness of multi-channel MAC protocols in terms of system utilization, system waiting times and system response times.

Our approach attempts to improve the utilization of the system by improving the service rates of the system. The system will therefore take less time to service a request than it would have if the effects of the MSC were still high. As a result more packets will be processed in a given time interval and long queues will not build up very fast.

The average waiting and system response times are also affected by the service rate of the system. If the service rates are good, customers will spend less time in the queue and in the system. The rate at which the customers would be serviced will be high. This can be achieved by improving the service time. Our scheme improves the service rate by reducing the idleness of the channels, reducing signalling overhead and by limiting the MSC to the first cycle. The value of the system service rate (μ) is very critical to the performance of the system. When the value of the service rate increases, utilization improves and delays are minimised. However, if it decreases, system performance degrades. The proposed CSA protocols will improve the performance of multi-channel MAC protocols with this concept.

5.1 Modelling the Control Channel

The multichannel MAC protocols implementing a single control channel can be modelled as a queuing network. The main emphasis is on the significance of the control channel and how it affects the performance of the network. Its significance can be related to the significance of the service rate which was shown above. This Section, therefore, characterizes the control channel as a service station with multiple input queues and multiple output queues. A well designed control channel is fundamental to improving the performance of the network.

The network has 3 distinct service points. The service points are depicted in Fig.5.3. These are the nodes marked Ns_1 to Ns_n , the control channel identified as Cc_1 and then the data channels marked Dc_1 to Dc_n . In the queuing model it can be seen that the control channel can slow down the speed of the network as a single service station fed by multiple servers and in turn sending its output to multiple servers. The capacity of the control channel therefore needs to be improved substantially. The control channel server should have reasonable capacity to offer well balanced service so that it can provide an efficient and very fast link to multiple servers at its input and output ends.

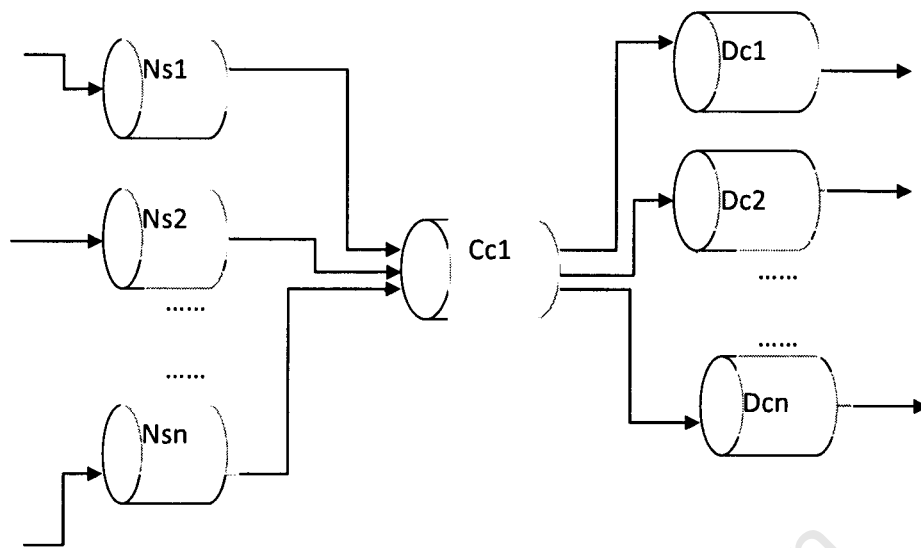


Figure 5. 3. A Multichannel queuing network with a single control channel server

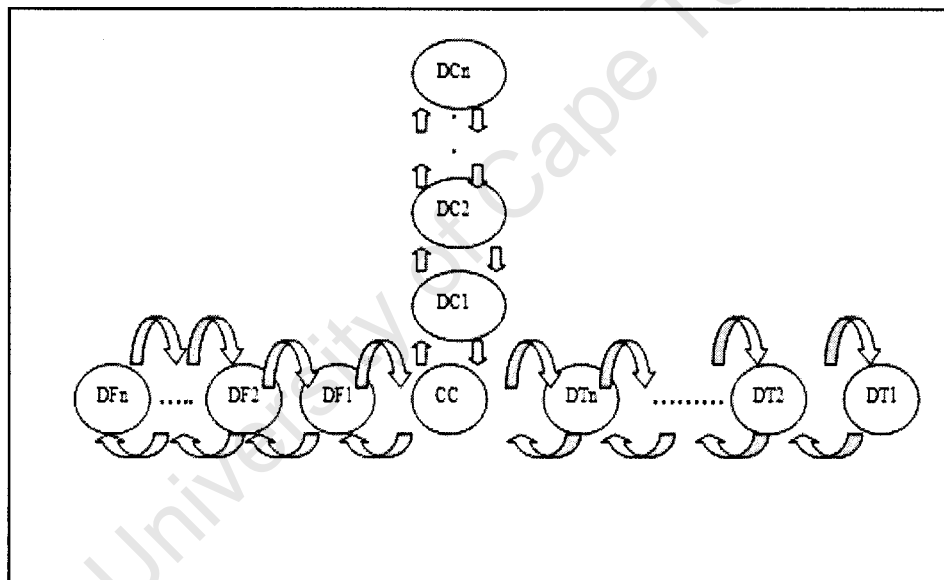


Figure 5. 4. A multiple scenario in multichannel systems with a single signalling channel

Figure 5.4 shows how the implementation of the common control channel as a single signalling channel results in the formation of multiple queues. Data packets are first queued when the nodes wait for the control channel to be free and contend for it. In our analysis, we consider these packets as data flows queued at the control channel which are denoted by DF1 to DF_n. When the data flow is de-queued from the control channel it is then placed in the data channel queue. Thereafter the data flows are served by the data channels. These two models clearly show the significance of the control channel in ensuring better performance of the multi-channel networks which implement the notion of a signalling channel.

In the following three figures, Fig 5.5, 5.6, and 5.7, we evaluate four multichannel MAC protocols which employ the idea of a control channel as a single signalling channel. We assume a Markovian packet arrival rate with an exponential inter arrival times. The arrival rate was assumed to vary between 0.1 and 2.9. The control channel service rate is based on the amount of time the control channel will service a transmitting pair which wants to reserve one of the available data channels. The service rates were based on the payload of the schemes primarily to show the effects of signalling on the capacity of the control channel. The payload is based on the number of control packets of each protocol. The payload was then translated into aggregated transmission time required to complete the control channel handshake for a given protocol. For the AMCP, we considered the worst case scenario for the control channel utilization in which all communicating pairs have to re-initiate data channel reservation after failed first attempts. This is according to the protocol which allows nodes to attempt to reserve a data channel available at both ends when the first attempt was not successfully. However, for both waiting and response times we assumed that all the initial attempts would be successful.

The following are of interest in our analysis of the schemes: system utilization, waiting time and the system response time. The system utilization is represented by Eqn (5.4). The Waiting time is represented by the Eqn (5.5) and finally, the system response time is represented by Eqn (5.6). The service rates of the multi-channel MAC protocols were based on the capacity of the control channel and signalling overhead of the individual protocols which were evaluated. The Little's Law was implemented in calculating the values of the above three parameters. The following multi-channel MAC protocols were evaluated: the Multichannel MAC (MMAC), the Local Coordination-based Multichannel MAC (LCM MAC), the Asynchronous Multichannel Coordination Protocol (AMCP) and the CSA.

$$\rho = \lambda / \mu \quad (5.4)$$

$$W = \frac{1}{\mu - \lambda} \quad (5.5)$$

$$L = \frac{\rho}{1 - \rho} = \frac{\lambda}{\mu - \lambda} \quad (5.6)$$

In Fig 5.5 we evaluate the utilization of the control channel in the four protocols, the MMAC, LCM, AMCP and the CSA. The MMAC had the worst utilization factor followed by the LCM. The AMCP and the CSA offer the best performance, however the CSA is superior. The low utilization factor shows that a given scheme has more capacity to handle increased volumes.

System utilization (ρ) depends on the service rates (μ). If the service rate is high, system utilization improves. If the service rate is low, then the utilization of the systems becomes poor. The MSC and the signalling overhead do degrade the service rates of the system which in turn affects the utilization of the system. Therefore, if both the MSC and the signalling overhead are reduced or eliminated, the utilization of the system is improved. The proposed scheme has the best utilization as it offers the best service rates.

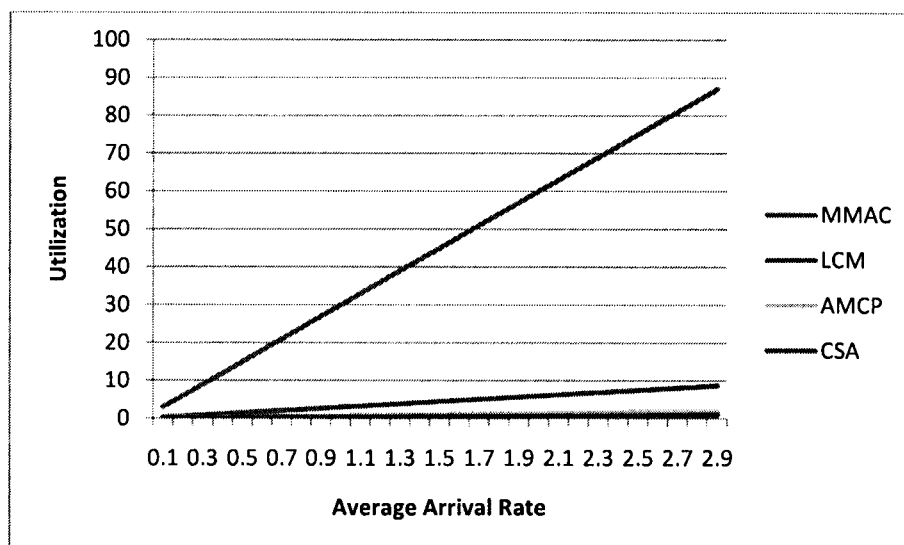


Figure 5. 5. The utilization of the control channel

The MMAC is not stable for the arrival rates that were considered in this analysis in both Figs. 5.6 and 5.7 because of its very low service rate. The results of MMAC are therefore not shown in these two figures.

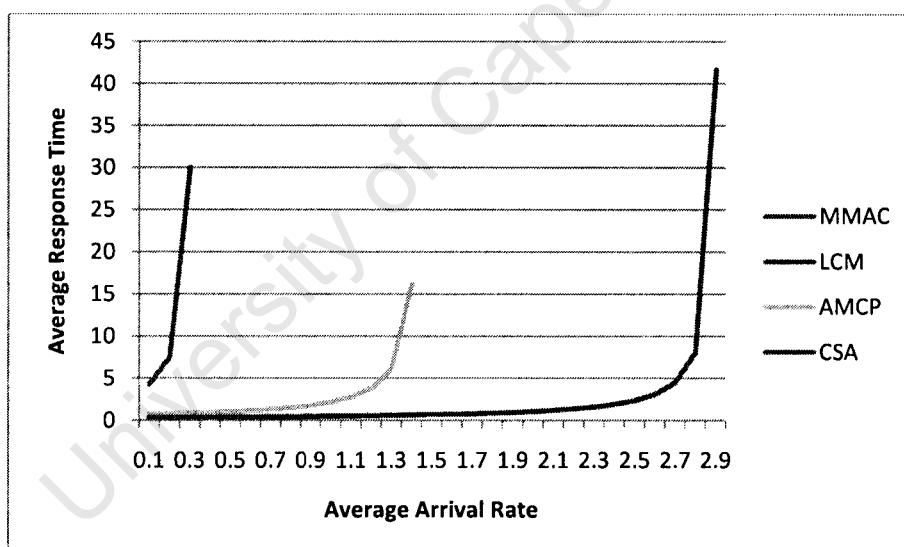


Figure 5. 6. Analysis of the response time

In Fig. 5.6 the CSA offered the best performance, the packets were subjected to the smallest amount of delay in the queue. It offered the fastest turnaround time as compared to the AMCP and LCM. The AMCP was the second best. When the systems offer the least delay in the system it shows that the service rate of the control channel is good and does not cause a significant degradation of the performance of the protocol. The LCM had the longest delay and therefore the control channel is likely to degrade significantly the performance of the network. The results of the MMAC are not shown due to its instability within the range considered for this analysis.

In Fig. 5.7 waiting time was considered. The waiting time is the time a packet spends in the queue. In this case, it is the amount of delay a packet is likely to be subjected to before it is processed and transmitted on the data channel. There was no significant difference between the waiting time and the system response time results. A similar trend was observed in the two graphs. However, the delays were slightly higher in Fig. 5.6 where both queue and service delays were considered.

The CSA is therefore effective in reducing the signalling delay of the control channel. The reduction of the signalling delay means that the capacity of the control channel has been improved and its scheduling capacity increased.

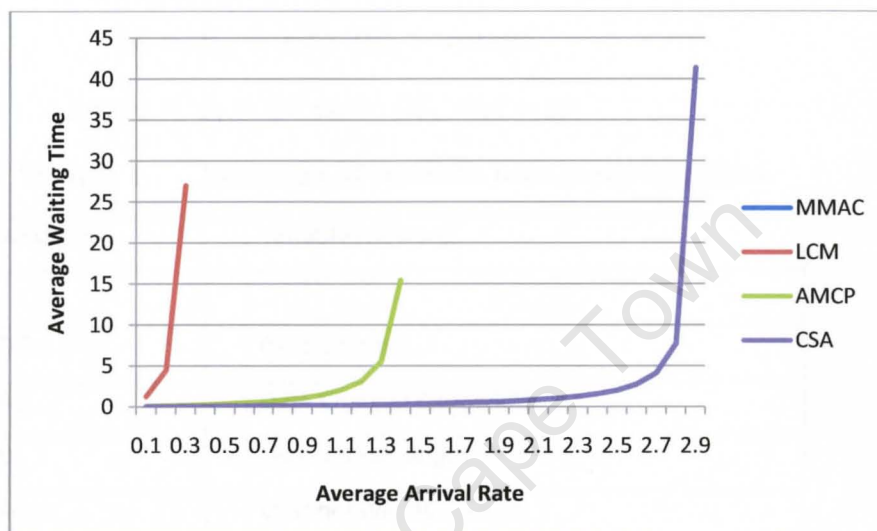


Figure 5. 7. The analysis of the system waiting time in the queue

5.2 Investigating the control saturation challenge

We have proven that the proposed CSA scheme does reduce the signalling overhead. The scheme also improves the utilization of channels. However, multi-channel MAC protocols which implement the idea of a dedicated control channel are assumed to cause a system bottleneck. The proposed scheme is therefore investigated to ascertain whether it is likely to cause any bottlenecks. The analysis did prove that a dedicated control channel does not result in system bottlenecks.

The channel saturation problem is investigated analytically. Both control and data channels are investigated. The number of data channels was increased from two to fourteen to investigate how increased capacity and congestion affects the capacity of the control channel. All the channels were assumed to have a bandwidth of 1Mbs. For testing purposes, the channels were assumed to be orthogonal.

It was noted that data channels transmit long packets as compared to the control channel. Data channels are also degraded by channel switching delays. The channel switching time and long data packets degrade severely the capacity of the data channels and cause them to

saturate ahead of the control channel. On the other hand, the shorter packets provide the control channel with more capacity to drive many data channels.

To investigate the capacity of the channels the following equations based on our proposed idea were employed. The equations capture the essence of our proposed scheme. The variables used in the equations are explained in Table 1. They express the durations of the data channel, control channel and the inter-cycle, respectively.

$$DC = B_{dc} - D_l + 2 * sw * DC_n - msc \quad (5.7)$$

$$CC = B_{cc} - hd * DC_n - Intcyc \quad (5.8)$$

$$Intcyc = D_l + 2 * sw - DC_n * hd - sw \quad (5.9)$$

Table 5. 1. Definition of variables used in the equations.

Variable	Variable Meaning
DC	Data Channel
B _{dc}	Data Channel Bandwidth
D _l	Data packet length
Sw	Channel switching delay
DC _n	Number of Data Channels
Msc	Multi-Channel scheduling cost
CC	Control Channel
B _{cc}	Control Channel Bandwidth
Hd	Control Channel handshake duration
Intcyc	Inter-cycle duration

Given the above equations, the capacities of both control and data channels were computed, allotment to nodes done and channel saturation investigated. All channels were considered to be having the same bandwidth of 1Mbs. Both data and basic rates were set to 1Mbs. The number of nodes was varied between 30 and 210 depending on the number of data channels. A system with 14 data channels had the largest topology. In the analysis, however, an average of 30 nodes and two data channels was considered in each case. In some cases the total number of nodes was considered.

In Fig. 5.8 a system with one control channel and two data channels was considered. The general topology had a total of 30 nodes. It was noted that the capacity of the 2 data channels caused a bottleneck in the system. Their combined capacity could support up to fourteen nodes. This translates to seven nodes per data channel. On the other hand the control channel had enough capacity for the 30 nodes.

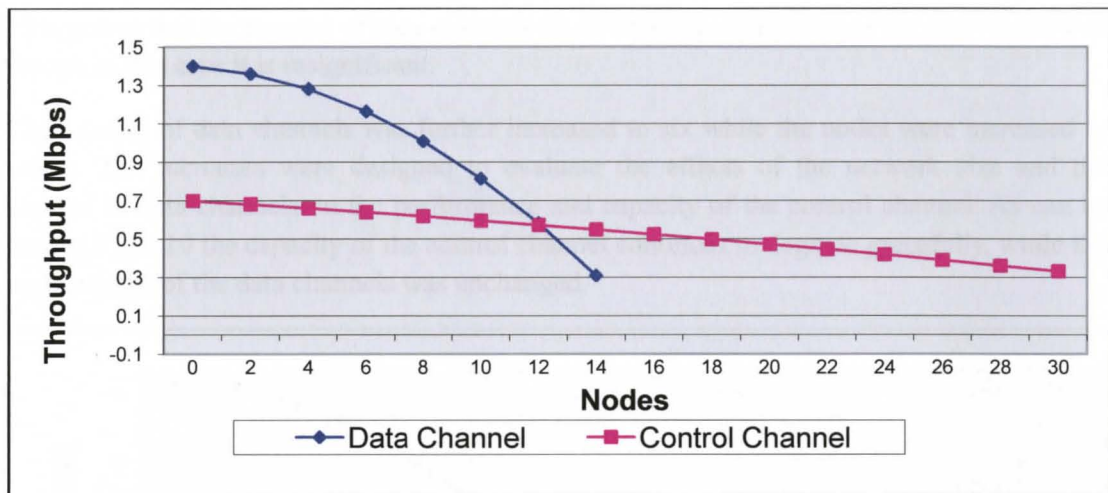


Figure 5. 8. Performance of the control channel when two data channels are considered

The inter-cycle has the longest duration in a two data channels system. Its duration reduces as the number of data channels is increased. The inter-cycle degrades the capacity of the control channel, when data channels are few and it improves the performance of the network when more data channels are added. It can be seen that the control channel is underutilized if there are very few data channels. The number of data channels should be steadily increased to improve the utilization of the control channel. At least four data channels should be considered.

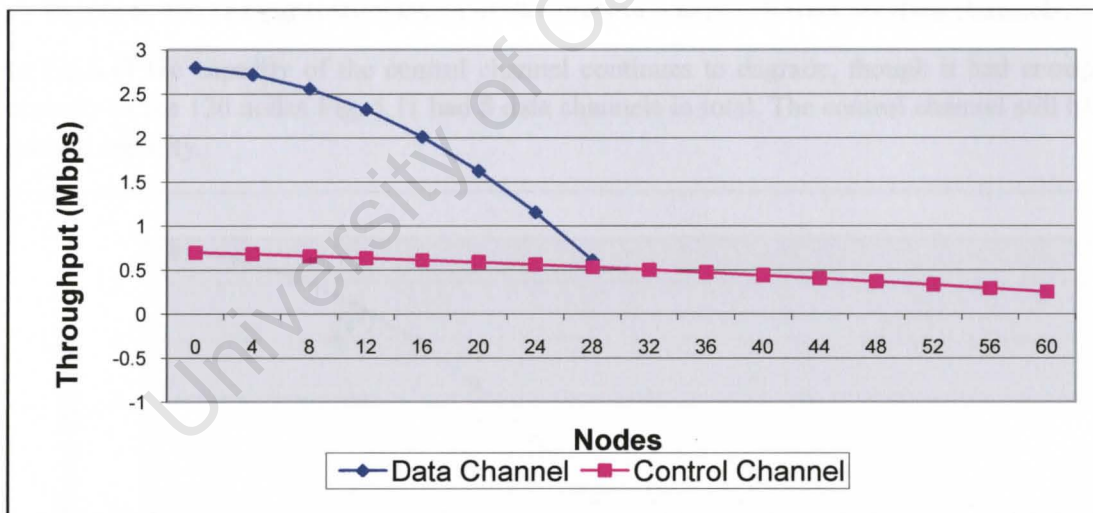


Figure 5. 9. Saturation levels in a system with four data channels.

When the number of data channels was increased to four in Fig.5.9, it was noted that the capacity of the control channel was still underutilized. On the other hand the number of nodes was increased to 60. The data channels saturated first and their performance was unchanged. However, there was small a change in the performance of the control channel.

This proves that the number of data channels do affect the performance of the control channel though in this case it is insignificant.

The number of data channels was further increased to six while the nodes were increased to ninety. The increases were designed to evaluate the effects of the network size and the number of data channels on the performance and capacity of the control channel. As can be seen in Fig.5.10 the capacity of the control channel continues to degrade gracefully, while the performance of the data channels was unchanged.

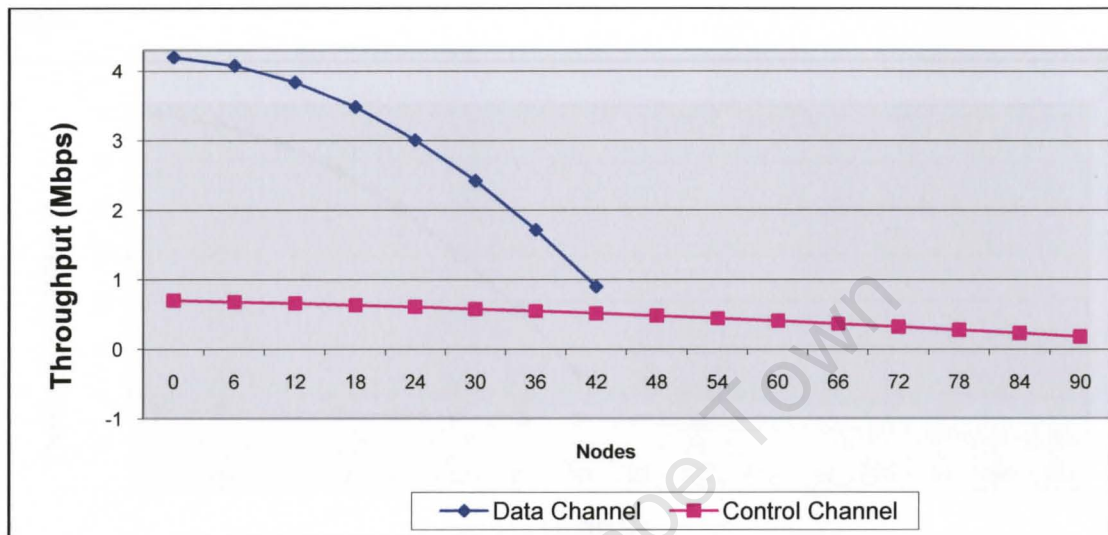


Figure 5. 10. The saturation levels of channels in a network with six data channels.

In Fig.5.11 the capacity of the control channel continues to degrade, though it had enough capacity of the 120 nodes Fig. 5.11 had 8 data channels in total. The control channel still had enough capacity.

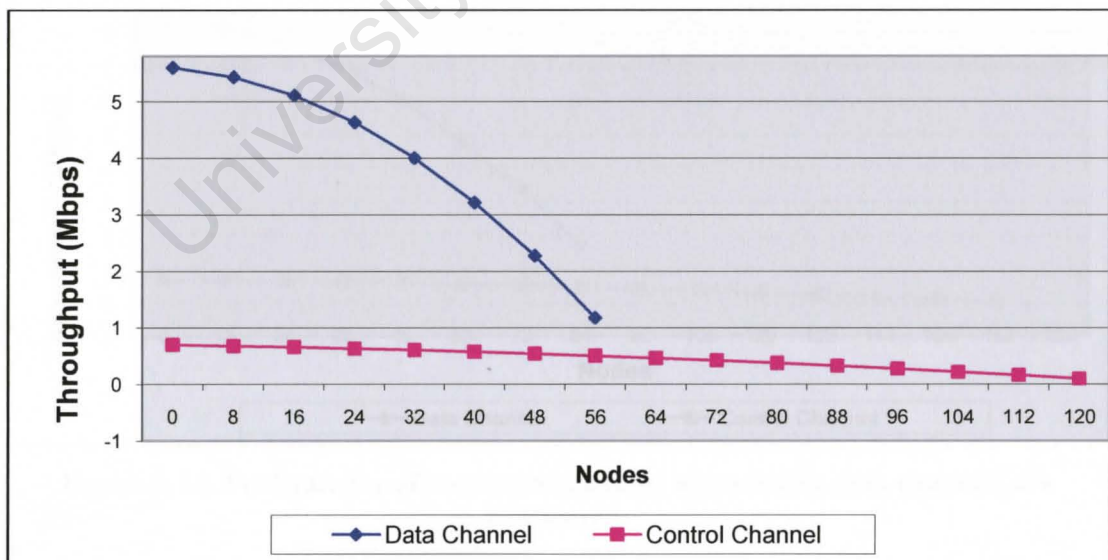


Figure 5. 11. The saturation point of the control channel

In Fig.5.12 the number of data channels was increased steadily to ten. The control channel could not drive all the data channels and its capacity was not enough for the 150 nodes. The control channel did not have adequate capacity for all the available nodes. When the data channels were fewer, the control channel was underutilized. It began degrading as the number of data channels was increased. To optimize the performance of the scheme, the number of the data channels should be increased to a level which does not underutilize the capacity of the control channel. On the same token, the control channel should run at a level which does not degrade the performance of the data channels. The optimal number of data channels is eight.

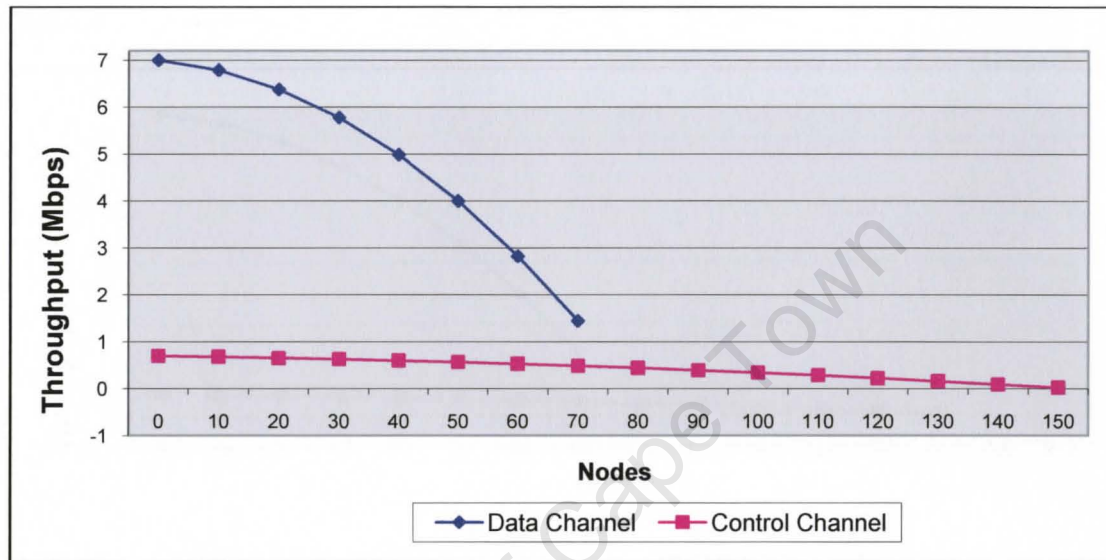


Figure 5. 12. Performance of the control channel when ten data channels are considered.

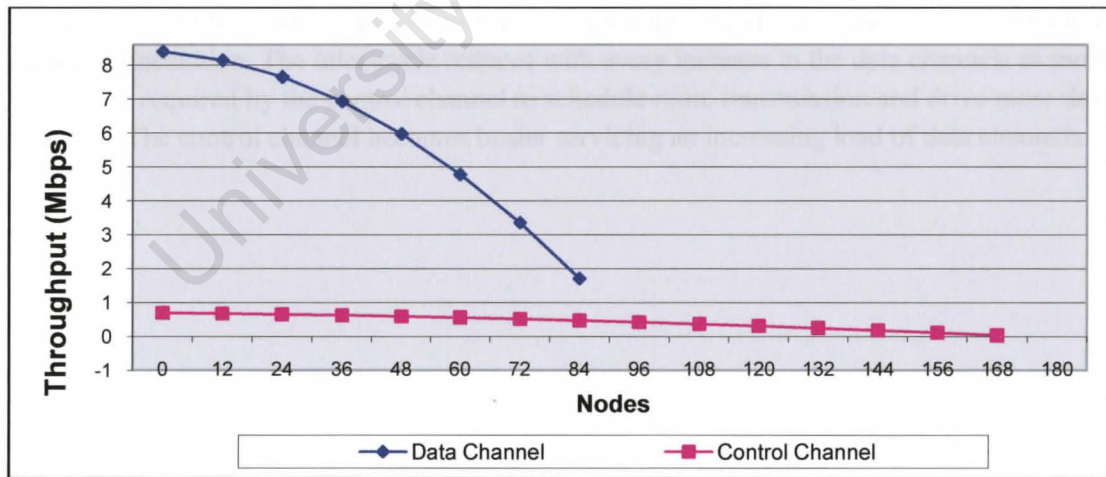


Figure 5. 13. Performance of the control channel when twelve data channels are considered.

The saturation of the control channel becomes more apparent in a system with twelve data channels. In a general topology with 180 nodes, the capacity of the control channel is limited

to only 168 nodes in Fig. 5.13. The impact of the saturation of the control channel becomes severe as more data channels are added. The saturation of the control channel at this stage does not degrade the performance the system. The performance of the system would have long been degraded by data channels which cause a system bottleneck after the 7th node on each data channel. To improve the system performance, higher data rates should be considered for the data channels.

In Fig. 5.14 similar observations were made. In this case, a total of fourteen data channels were considered. The topology had 210 nodes. The combined capacity of data channels was only enough for ninety-eight nodes. The control channel could support 182 nodes instead of 210.

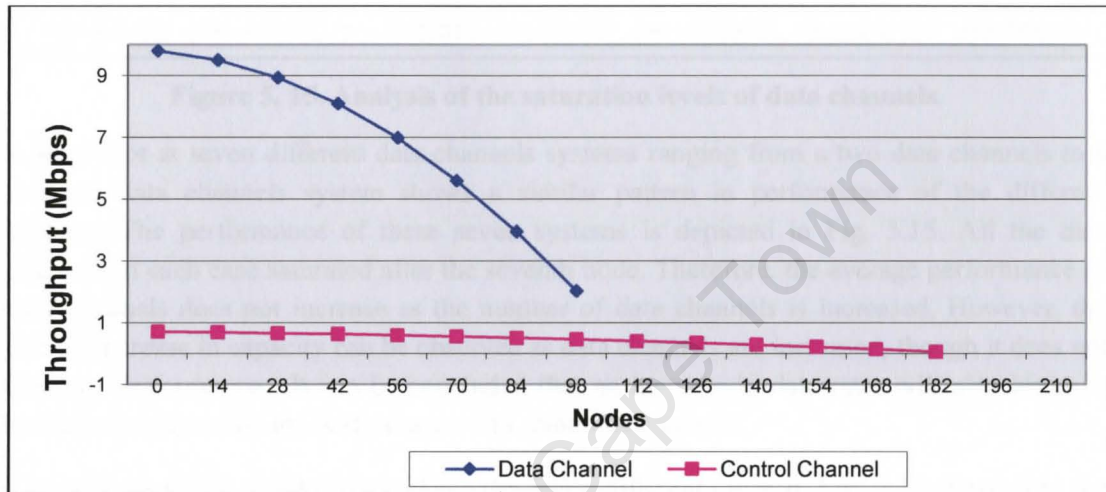


Figure 5. 14. Performance of the control channel when fourteen data channels are considered.

The network with 14 data channels in Fig 5.14 provided the shortest inter-cycle duration in our experimentation. The inter-cycle reduces with every increase in the data channels as more capacity is required by the control channel to schedule more transmission and drive more data channels. The control channel becomes busier servicing an increasing load of data channels.

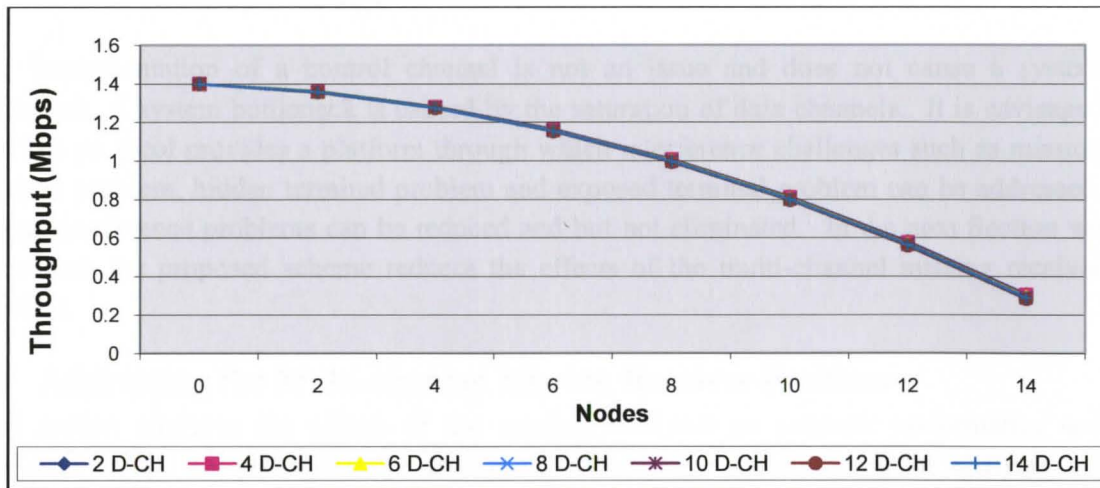


Figure 5. 15. Analysis of the saturation levels of data channels.

A snap shot at seven different data channels systems ranging from a two data channels to a fourteen data channels system shows a similar pattern in performance of the different systems. The performance of these seven systems is depicted in Fig. 5.15. All the data channels in each case saturated after the seventh node. Therefore, the average performance of data channels does not increase as the number of data channels is increased. However, the overall increase in capacity can be observed as data channels are increased, though it does not improve performance. It can be concluded that an increase in data rates will also improve system capacity while the performance will remain unchanged.

The analysis of the control channel for the seven different cases in Fig. 5.16 shows that the control channel degrades gracefully as the number of the data channels is increased. The performance and capacity of the control channel is affected by the number of data channels. Its performance reduces with every increase in data channels. It should be noted that despite the degradation of the control channel, it still had enough capacity to drive as many as fourteen data channels.

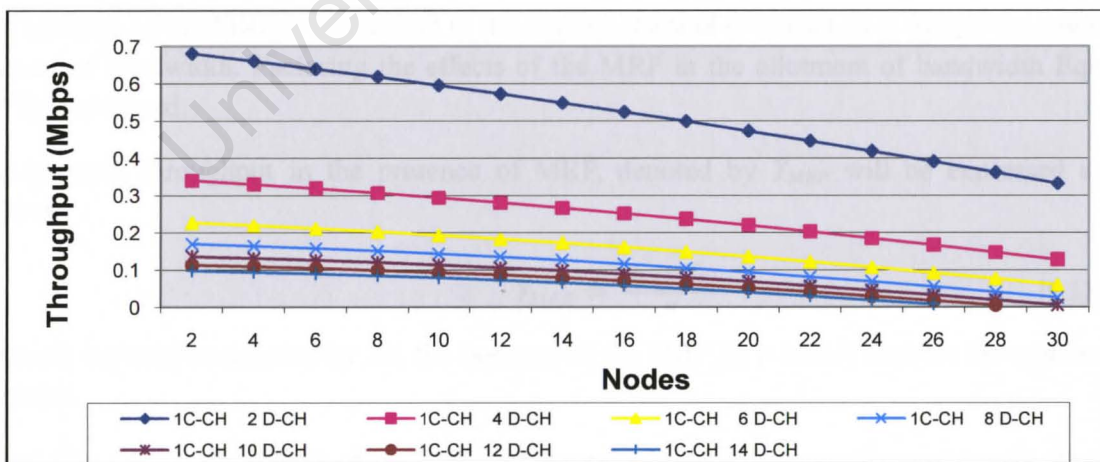


Figure 5. 16. Analysis of the capacity of control channel as data channels are increased from two to fourteen.

The implementation of a control channel is not an issue and does not cause a system bottleneck. A system bottleneck is caused by the saturation of data channels. It is envisaged that this protocol provides a platform through which interference challenges such as missing receiver problem, hidden terminal problem and exposed terminal problem can be addressed. These interference problems can be reduced and but not eliminated. In the next Section we show how the proposed scheme reduces the effects of the multi-channel missing receiver problem.

5.3 Addressing the Multi-channel Missing Receiver Problem

This section analyzes the effects of the missing receivers on network performance and analytical results are presented. We discuss the assumptions underpinning the analysis, we then present and discuss the results.

Throughput y , which is available to each node in the network, is given by dividing the capacity of the network by the number of nodes in the network [35]. Given this formula, the allotment of throughput to the nodes can be ascertained and predicted. The equation is given below; c is the capacity, N denotes the number of nodes.

$$y = c/N \quad (5.10)$$

In the multi-channel environment, the capacity of the network increases with the number of channels implemented. It increases approximately at N times the channel capacity. Nc is therefore the total capacity of all the channels.

It is argued in [2] that a dedicated control channel in a three channel system constitutes a third of the total capacity. Generalizing the capacity of the control channel C_c , with M , the number of channels, the following formula was obtained:

$$C_c = \frac{N_c}{M}, \text{ Where } M \text{ is } 3 \quad (5.11)$$

The instance of the MRP is equivalent to the control channel overhead as it wastes the same amount of bandwidth. Factoring the effects of the MRP in the allotment of bandwidth Eqn (5.12) is obtained.

The network throughput in the presence of MRP, denoted by Y_{MRP} will be expressed as follows:

$$Y_{MRP} = \frac{N_c (1 - \frac{n}{M})}{N} \quad (5.12)$$

Network capacity is denoted by Nc , the instance of the MRP by n and N denotes the number of nodes.

Given Eqn (5.12), the effects of the MRP can be modelled. If there are three channels, then one encounter of a missing receiver will result in one third degradation of network throughput.

Two encounters of deafness in our proposed CSA will result in two-thirds throughput degradation. Fig. 5.17 depicts network throughput degradation under these assumptions, when Capacity is set to 12 Mbps and M to 3. Y_{MRP} denotes throughput in the presence of MRP.

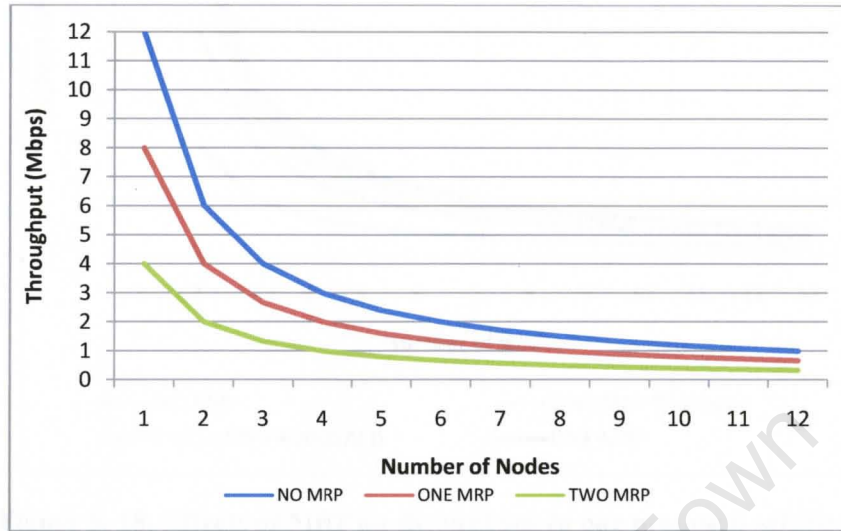


Figure 5. 17. Effects of MRP on throughput.

When the actual transmission durations of the control and the data channels are considered, it becomes apparent that the effects of the MRP would be less severe. The transmission ratio of the control channel to the data channel is approximately 11 to 1 in terms of transmission durations taking into consideration the channel switching delay. The results of an 11 to 1 ratio are expected to differ significantly from the results obtained in Fig 5.17 which are based on a 2 to 1 ratio. The instance of a MRP will cause a 12th of network degradation.

Control channel overhead is represented by Eqn (5.10), when M is set to 12.

To calculate the network throughput after factoring the effects of the node deafness problem, Eqn (5.12) is employed. When an RTS is sent to a deaf node, a complete RTS/CTS handshake is recorded as a complete transmission amounting to a control channel overhead.

The amount of bandwidth utilized is therefore equal to the control channel overhead. The assumption that an instance of a MRP amounts to the control overhead is valid as the control channel would be unavailable for the entire duration of the RTS/CTS handshake.

The overhead caused by the instance of the MRP now translates to $\frac{n}{12}$. Substituting this fraction it into Eqn (5.12), we get the following equation.

$$Y_{MRP} = \frac{N_c (1 - \frac{n}{12})}{N} \quad (5.13)$$

Given Eqn (5.13) and that N_c is 12 Mbps and M is 12; the results in Fig 5.18 were obtained.

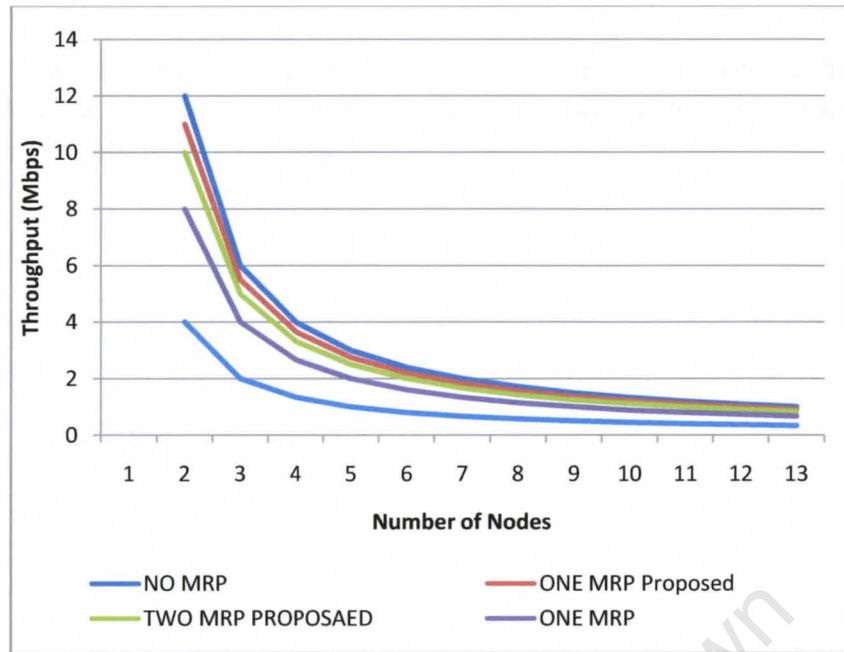


Figure 5. 18. Effects of MRP on throughput in our proposed solution.

Fig 5.18 shows that our proposed approach is likely to perform better in the face of Missing Receivers and its performance would improve as more instances of MRP are encountered. For example in Fig 5.18 where two instances of node deafness were encountered, our proposed approach performed better than when only one instance was encountered. However, in a given cycle, at most two terminals may be deaf and unreachable, according to our CSA assumptions for a network with three channels.

The solution to MRP will improve the network throughput and reduce significantly the control channel overhead cost. Fig 5.18 shows that the instances of missing receivers do increase the overhead of the control channel. It can also be seen in the same figure that the effects of node deafness in our proposed architecture will be less severe as compared to Fig 5.17.

5.4 Summary

The proposed CSA was modelled and evaluated using the Queuing networks and Markov Chains. The models clearly show the significance of both the service rate and the control channel in improving the performance of multi-channel MAC protocols. The proposed CSA scheme does reduce the signalling overhead costs. It also improves the utilization of channels. The CSA is an effective and efficient multi-channel MAC protocols. It solves the coordination, channel selection, channel scheduling and channel assignment challenges of multi-channel MAC protocols. Furthermore, it addresses the new multi-channel challenge, the multi-channel scheduling cost (MSC).

The CSA is also optimized for other multi-channel interference challenges such as the multi-channel missing receiver problem and the multi-channel hidden terminal problem. It was

demonstrated how the CSA scheme minimizes the impact of the multi-channel missing receiver problem. In addition, the implementation of the support network structure solves these multi-channel interference challenges.

University of Cape Town

Chapter 6 Simulation Results of the Proposed Scheme

6.0 Introduction

In this chapter, the performance of the proposed cyclic scheduling algorithm (CSA) is evaluated through Network Simulator 2 (NS 2) simulations. The effect of the switching time was investigated through simulations before the CSA scheme was implemented. The switching time results show a severe degradation of multi-channel MAC protocols. The impact of the switching time and the signalling overhead cost justify the need for efficient MAC protocols. The proposed CSA scheme addresses these challenges. It reduces the signalling overhead, limits the MSC to the first cycle and associates all the switching times with the data channels.

The following metrics were used to evaluate the scheme: throughput, packet drop rate and the dropped packets. The scheme is compared with the AMCP [3]. The AMCP was compared recently to three other schemes and was found to be superior. The AMCP is considered to be a leading protocol judging from the results in the literature and its design attributes. To evaluate the effectiveness and the scalability of the proposed scheme, a number of different network sizes were considered. A total of six different network sizes were considered. The network sizes range from a smallest network with 4 nodes to the largest with 30 active nodes. In some instances, we refer to network size in terms of data flows. A flow joins two nodes.

We begin by showing the effects of the channel switching time on the performance of the network. We then show how the proposed CSA improves the performance of multi-channel MAC protocols. The work we did in single channel MAC protocols is also presented and evaluated in this chapter. The single channel MAC is discussed to highlight the importance and benefits of reconfiguring the EIFS in both single and multi-channel MAC protocols. The single channel also justifies the need to implement an Inter-Frame Space which is suitable for multi-channel MAC protocols. Lastly, we discuss and evaluate the CIFS scheme.

6.1 Simulation Model

The NS 2 was employed to simulate all the protocols which were considered in this project. Furthermore, IEEE 802.11 MAC standard, which is implemented in NS 2, was considered for all the simulations. The detailed simulation models and parameters for each scenario are discussed in the following sections. In all the multi-channel scenarios, a total of 5 channels were considered. One channel was set aside as a signalling channel and the rest as data channels. The 5 channels were assumed to be equal, each offering a bandwidth of 2 Mbps.

The 5 channels were assumed to be orthogonal for experimentation purposes. The switching delay was set to 22 μ s. The nodes incur a delay of 224 μ s when they switch onto the data channel and another delay of the same magnitude when they switch back onto the control channel. The NO Ad Hoc (NOAH) routing agent was implemented in multi-channel scenarios.

The sizes of the networks were varied to evaluate effectively the efficiency of the proposed scheme, the impact of the switching time and the MSC. A total of 6 different networks were

considered for each scenario. The smallest network had four nodes and the largest network had thirty nodes. The topologies of all the networks were general. For each network size, at least ten simulation runs were considered with each simulation running for three hundred seconds, simulation time. The different network sizes were either expressed in terms of the number of terminals or the number of data flows. The number of terminals was always twice the number of data flows. A data flow is a link between two distinct terminals. The detailed list of parameters and their respective values is shown in Table 6.1. In Section 6.2, we verify the theoretical results generated in Chapter 5.

Table 6. 1. MAC Layer and other Parameter Settings

Parameter	Value
SIFS	10 μ s
DIFS	50 μ s
EIFS	364 μ s
CIFS	56 (μ s)
Slot time	20 μ s
Data rate	2 Mbps
Basic rate	2 Mbps
Channels	2,3,4,5,6,7,8,9,10,11,12,13,14,15
Switching time	224 μ s
Packet size	1000 bytes
CW _{max}	1023
CW _{min}	7
Short Retry Limit	7
Long Retry Limit	4
PLCP Length	192 bits
PLCP rate	1 Mbps
RTS	20 bytes
CTS	14 bytes
ACK	14 bytes
MAC Header - Data	28 bytes
MAC Header rate	Basic rate
Routing Agent	NOAH
Network Sizes	4,5,6,8,10 and 30 nodes

6.2 Verification of the theoretical results

In this section we confirm the theoretical results presented and discussed in chapter 5 through computer simulations. The parameter settings are shown in Table 6.1. The behaviour of the control channel and its performance as the number of channels is increased is verified. The improvements of service rates and the reduction of transmission delays by the proposed scheme is verified in Section 6.4

Fig 6.1 shows the average achieved throughput by a network with ten nodes. The performance of the network was investigated in 14 different scenarios. The number of channels was changed in each scenario. The first scenario had two channels and thereafter the number of channels was incremented by one until the last scenario with 15 channels was considered. It was observed that the performance of the network kept on improving as the

number of channels was increased until the sixth channel; thereafter it remained almost constant with very minor fluctuations.

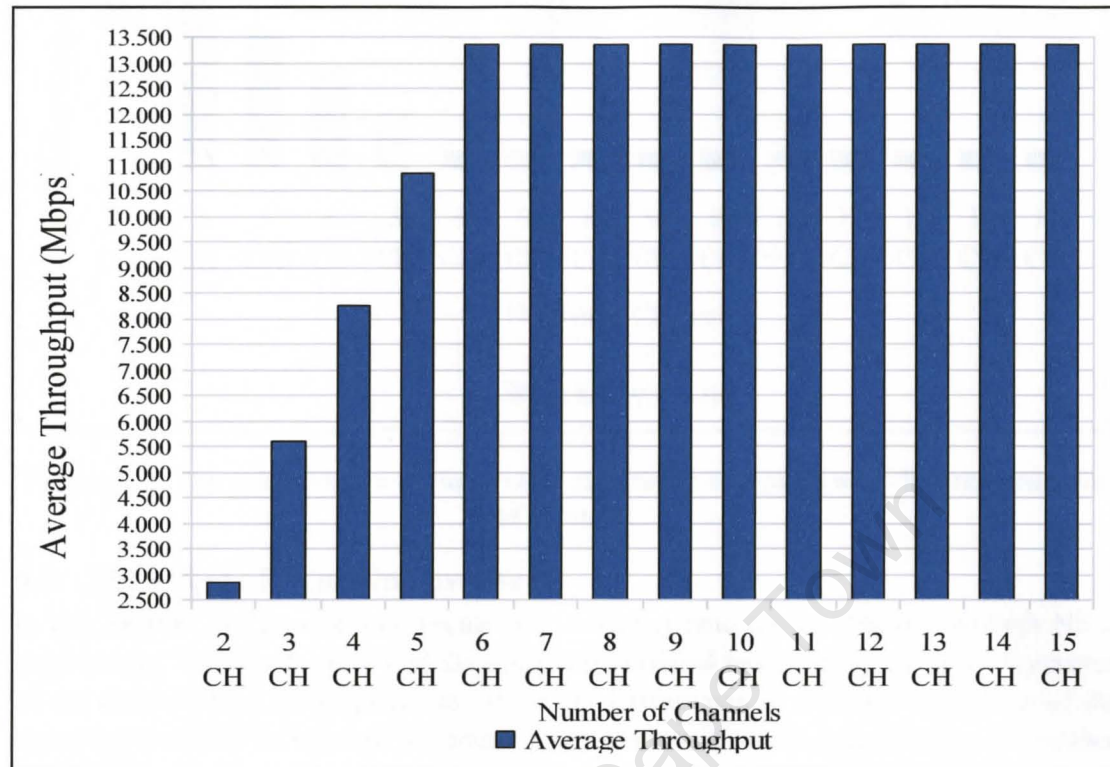


Figure 6. 1. The average achieved throughput in a network with 6 nodes investigated under 14 different scenarios.

The results confirm that the control channel approach degrades the performance of the network when few channels are implemented. Network performance improves with the increase in the number of channels before it plateaus. However, the performance of the control channel is expected to worsen as more channels are added. This agrees with the theoretical results discussed chapter 5.

In figure 6.2 the performance of the control channel was investigated under the same scenarios as in Figure 6.1. The emphasis of the investigations was on the amount of delay incurred as the number of channels is increased. Packet drop rate was employed to investigate and analyze the performance of the control channel in such scenarios. It was observed that the increase in the number of channels improved the performance of the network. The performance of the network was poor when fewer channels were implemented. It performed well when at least six channels were employed. The performance of the control channel is expected to degrade as the number of channels is increased beyond 15. However, spatial reuse is likely to keep its performance constant as more channels are added.

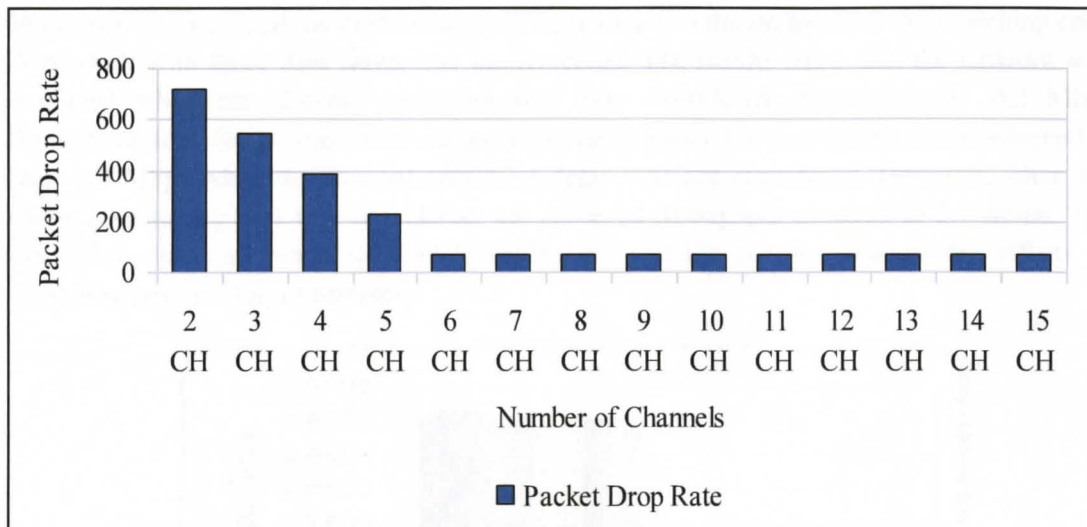


Figure 6. 2. The performance of the control channel in scenarios with different number of channels

6.3 The effect of signalling overhead

In this Section, we present and discuss the switching time results obtained through NS 2 experiments. The results show that the signalling overhead has an effect on the performance of the multi-channel MAC protocols. The main interest was to evaluate the impact of the signalling overhead on network performance as the network load increased. The performance of the network was investigated under the following two scenarios the “with switching” and “without switching”. The “with switching” scenario considered a switching time of 224 μ s, and it shows a severe degradation of the performance of the network.

The “without switching” depicts an implementation with no channel switching component and “with switching” depicts an implementation which has factored in the channel switching penalty. The performance of the network under these two setups was contrasted as the number of data flows or the network size was increased. Fig 6.3 shows the effects of the switching cost in a network with 3 data flows.

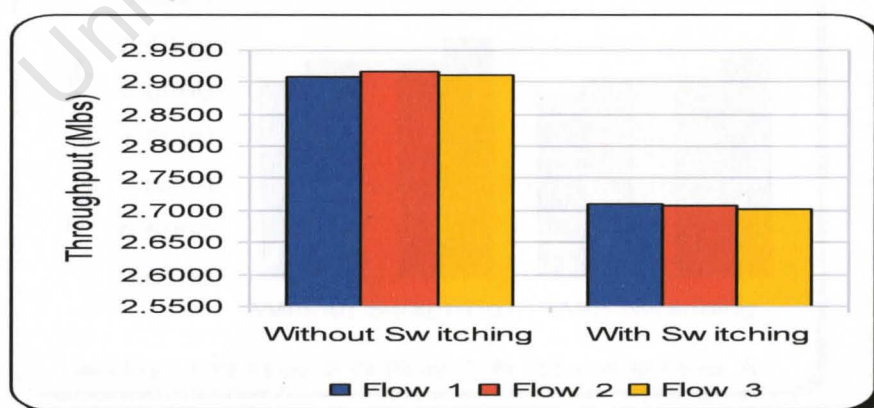


Figure 6. 3. The effect of switching cost on a network with three data flows.

In Fig 6.3 we evaluated the performance of the network in the presence of the switching cost. A network with three data flows was implemented. The results show that the network was degraded when the channel switching cost was considered. Approximately 0.2 Mbps throughput degradation was observed on all the three flows. On average all flows achieved at least 2.9 Mbps when the channel switching delay was not considered. However, when the channel switching cost was considered, the achieved throughput dropped to 2.7 Mbps. The size of the network was increased to eight nodes in Fig 6.4, to evaluate the effects of switching cost in a larger network.

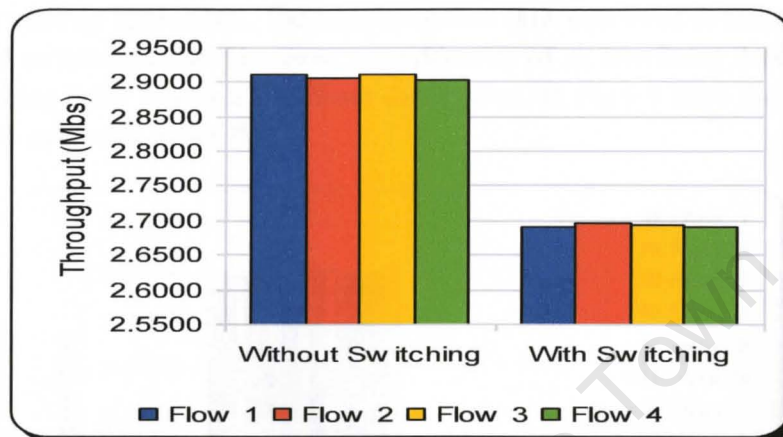


Figure 6. 4. Degradation of network in a network with four data flows.

A similar trend to Fig 6.3 was also observed in Fig 6.4. However, in this case the achieved throughput in the presence of the channel switching delay was further degraded. All the flows achieved less than 2.7Mbps throughput. When the channel switching penalty was not included, almost the same throughput as in Fig 6.3 was achieved. The increase in the number of the data flows from three to four degraded the performance of the network further. The next results in Fig 6.5 reinforce this analysis though with a variation on the results without the switching delay.

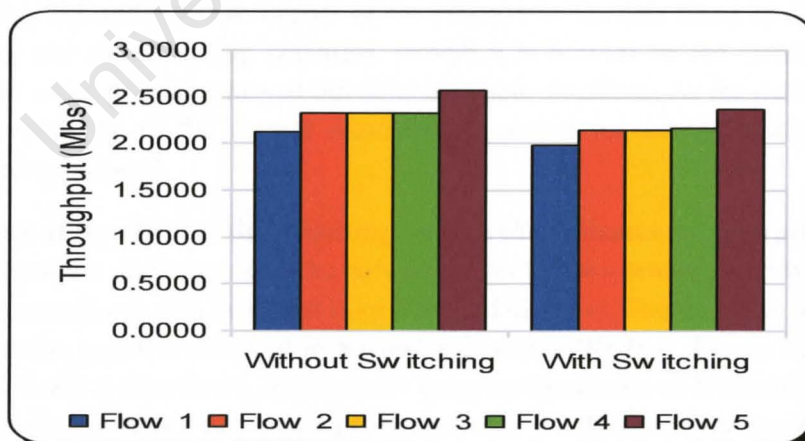


Figure 6. 5. The effects of an interfering data flow on switching and non-switching.

A network with five data flows exhibited a distinct set of results. There was no marked difference between the two operating environments. Both situations recorded significant throughput degradation. The results for a switching penalty were slightly lower though. This suggests another factor which was responsible for this degradation. If it were caused by the channel switching penalty the results of Fig 6.5 would be similar to the earlier results.

In Fig 6.5, we had four data channels which were shared by five data flows. There was always one extra data flow at any given time interfering with the other four data flows. Interestingly a degradation caused by an interfering data flow is severe on both the switching and the non-switching approaches. The interfering data flow was more severe than the effect of the channel switching delay. However, a combination of an interfering data flow and the channel switching delay causes a significant degradation. In Fig 6.6 show the results of the largest network evaluated in this thesis.

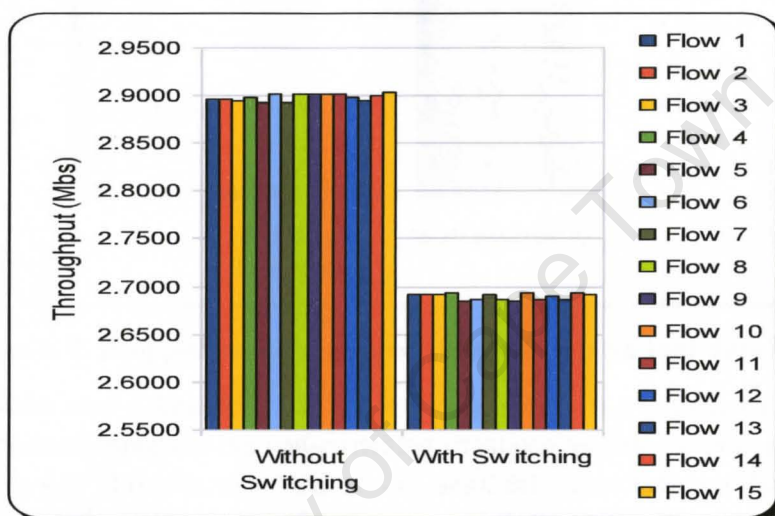


Figure 6. 6. The performance of the network with fifteen data flows.

The results of a general network with fifteen data flows in Fig 6.6 exhibited similar trends as observed in Figs 6.3 and 6.4. The impact of the increase in the data flows is noticeable on both switching and non-switching scenarios, though it is heavier on the “with switching” scenario. There was a drop in achieved throughput in both situations. As the data flows were increased, the capacity of the control channel was eroded impacting negatively on the performance of the network.

6.2.1 Analysis of the effect of the switching time on the utilization of network resources

We also evaluated the performance of the network under the two setups in terms of dropped packets. The network was also increased from 3 to 15 data flows. The results in this category exhibited a similar patterns observed in Section 6.2 above. We first discuss the results of networks with 4 and 5 data flows, and then we compare the results of the smallest network with 4 terminals to the largest network with 30 terminals. We then compare the results of the smallest network to the largest network. The rest are similar to the results of a general network with four data flows as observed above.

More packets were dropped for the switching situation than they were for the non-switching case. This is evident in Fig 6.7, where a number of packets were dropped when the channel switching penalty was included. This was caused by longer waiting durations imposed by the switching delay. The impact of the switching delay is more apparent when we consider dropped packets. This highlights the need to reduce the impact of the switching delay and signalling cost to improve the performance of the control channel. When these delays are reduced, network performance may be improved significantly. In figure 6.7, the results of a network with 4 data flows are shown.

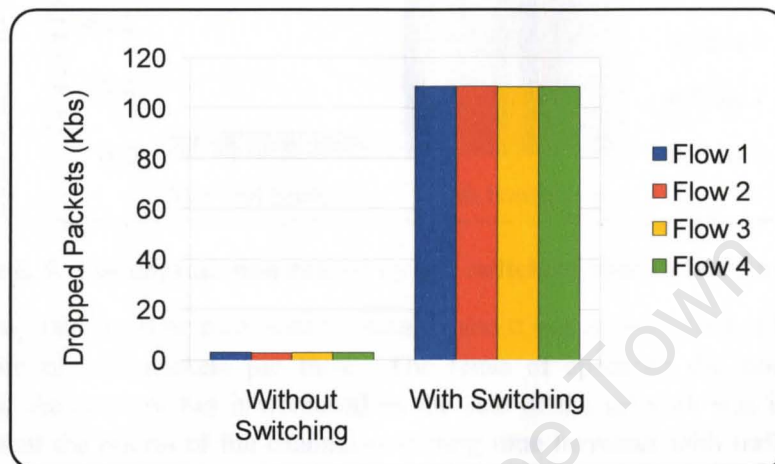


Figure 6. 7. Dropped packets in a general network with four data flows

A general network with 5 data flows like the one in the section 6.4 exhibited a peculiar set of results. Both the switching and the non-switching situations recorded significant packet loss as shown in Fig 6.8. However, there was a very small difference between the two. We also attribute these significant losses in both scenarios and their small difference in performance to the interfering fifth data flow. These results validate our claim we made in the analysis of Fig. 6.5 results.

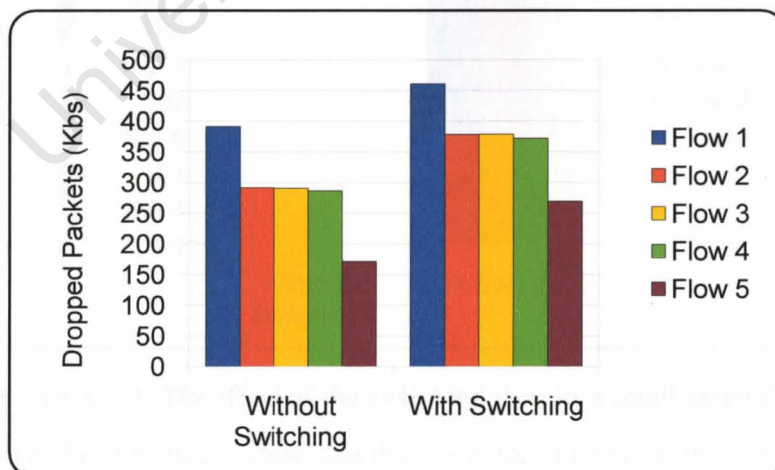


Figure 6. 8. The total number of packets dropped in a network with five data flows

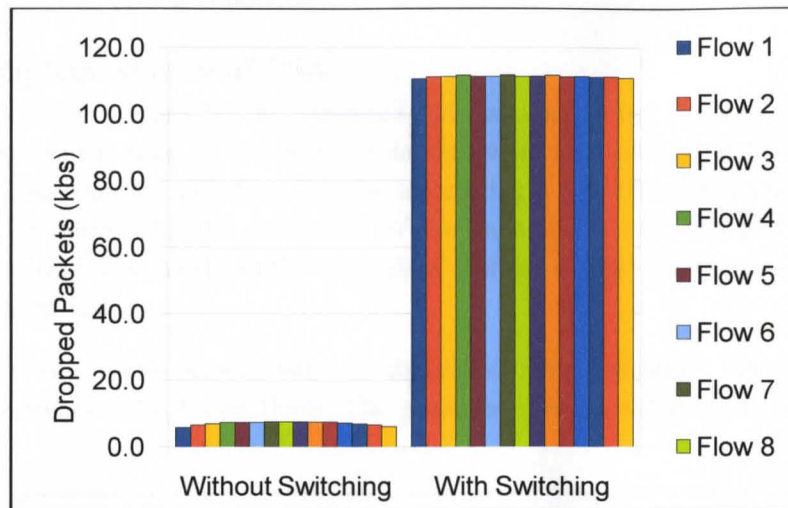


Figure 6. 9. The degradation caused by the switching time in large network

The packet drop rate per flow continued to increase and it was at its highest in Fig 6.9. It was close to a rate of 120 packets per flow. The reuse of spectrum did not improve the performance of the network but it worsened as the size of the network was increased. The results show that the effects of the channel switching time increases with traffic load in the network. It degrades significantly larger networks (Fig 6.9) than it does smaller networks (Fig 6.10). This can be seen in Fig 6.10, the smallest network size which was considered in this simulation. Packets were dropped at a rate of 103 packets per flow. The effect of the channel switching time is therefore severe in large networks. A channel switching time solution is sought to improve the scalability of networks and to improve the performance of the multi channel MAC protocols in large networks.

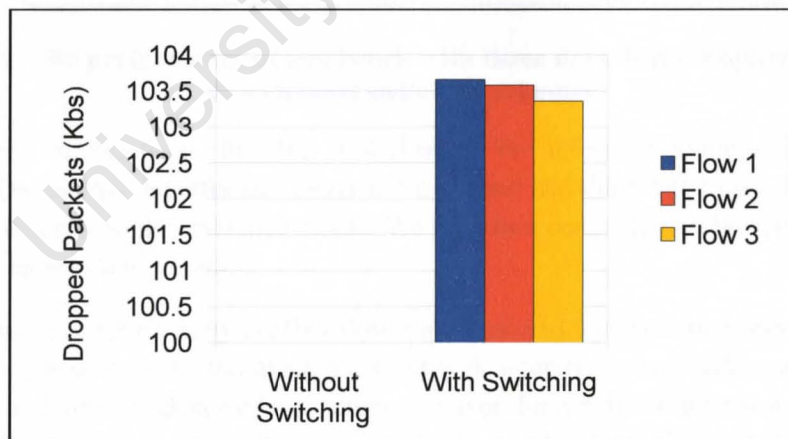


Figure 6. 10. The effect of the switching time in a small network

The results in this Section clearly show that there is a need to address the channel switching time, the signalling overhead and the MSC. The simulation focussed on the effects of the switching time. However, the MSC and the signalling overhead challenges were also at play.

In the next Section, we simulate and discuss the results of the proposed CSA which addresses these challenges. The CSA is compared to the AMCP.

6.4 The implementation of CSA

The results of the proposed CSA are presented and discussed in this Section. The simulation model and parameters used in the previous section were also utilized in this Section. The CSA scheme addresses the switching time by associating it with the data channels. The MSC is addressed by improving the utilization of the capacity of channels and reducing the signalling overhead. The results of the CSA show that the effects of these challenges can be reduced or minimized.

Five channels were implemented with one dedicated control channel. Fig 6.11 depict the results of a network with 3 data flows. The proposed scheme did perform better than the AMCP.

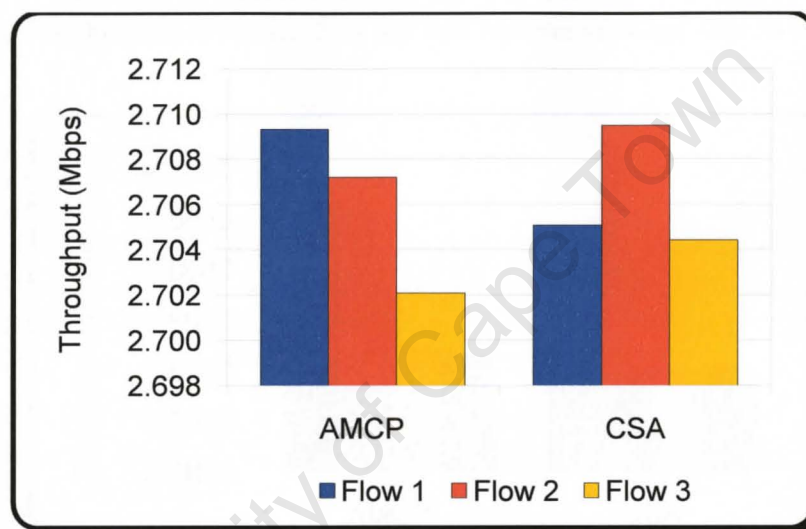


Figure 6. 11. The performance of a network with three data flows subjected under the two channel switching schemes

It can be seen in Fig 6.11 that the first flow in the reference model achieved higher throughput. Our approach performed better in the second and third data flows. In general, our scheme was superior to the reference model. We therefore conclude that for a three data flow network, our approach is superior.

The low throughput achieved by the first flow was caused by longer data transmissions in our reconfigured approach. In the initial stages of network setup there was high contention for the first channel and high incidence of interferences. Given longer data transmission durations in our scheme, the degradation becomes worse as evidenced by the achieved throughput for the first data flow. For the second and third data flows our model performed better its performance improves with either an increase in data channels or data flows.

In Fig 6.11, the number of data channels was more than the number of data flows. This resulted in the highest achieved throughput as compared to the subsequent results where data

flows were either equal to or more than the number of data channels. The highest achieved throughput in Fig 6.11 was therefore possible due to less interference experienced in a network with 3 data flows.

Fig 6.12 present results obtained in a network with 4 data flows. There was one to one pairing of data channels to data flows. It can be noted that there was a slight decrease in achieved throughput in the two schemes. The decrease in achieved throughput was caused by the non availability of one extra data channel. The data flows did not benefit from the extra data channel which resulted in a decrease in achieved throughput.

In Fig 6.12, the reference model was superior to our model in all the data flows. It achieved higher throughput in all the cases. This means that, where there is less interference, for example, the number of data channels is equal to the number of data flows; the performance of our model is poor. On the other hand, when there is an increase in interference, the performance of the proposed scheme becomes superior. It scales well and performs better in congested and backlogged networks. This fact will become more apparent in the next sets of results.

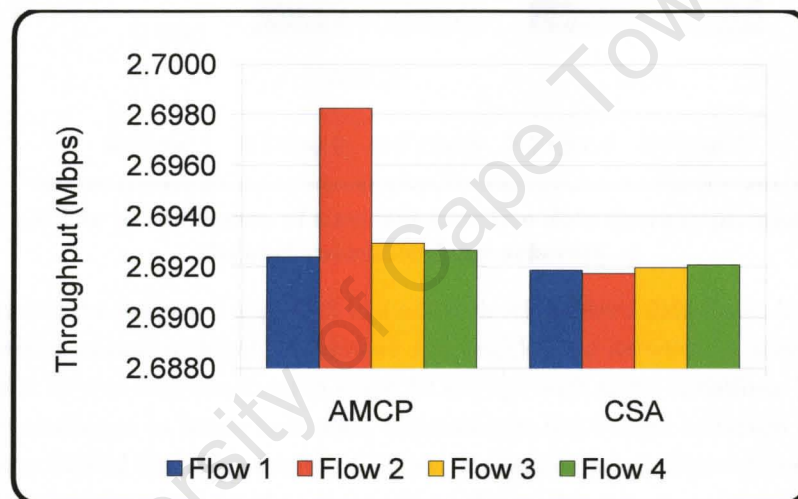


Figure 6. 12. Comparison of two switching approaches with four data flows.

In Fig 6.13, we analyse the performance of our approach in a general network with 10 data flows. The data flows are more than the available data channels. This setup increases the amount of interference in the network. The interference caused a further decrease in achieved throughput. Our approach, however, performed better, which is consistent with the observation made in the interpretation of Fig 6.12 results. It was only outperformed in the first data flow. The reason cited for the poor performance of the first node in Fig 6.11, is also applicable here.

When the network is setup, before data flows have sufficient information about the state of the network and the knowledge of other data flows, there is bound to be more contention for the first channel. This will increase interference on the first data channel, exerting a negative impact on achieved throughput. This incidence has a higher effect in our model because of

longer data transmission durations employed. Two channel switching delays have been added to the duration of the data transmission, which by design are longer.

The proposed approach performed reasonably well for the last four data flows. The achieved throughput is more than the one achieved in the reference model. The results depicted in Fig 6.13 are similar to the results presented in Fig 6.11. The only difference is the achieved throughput by the given data flows.

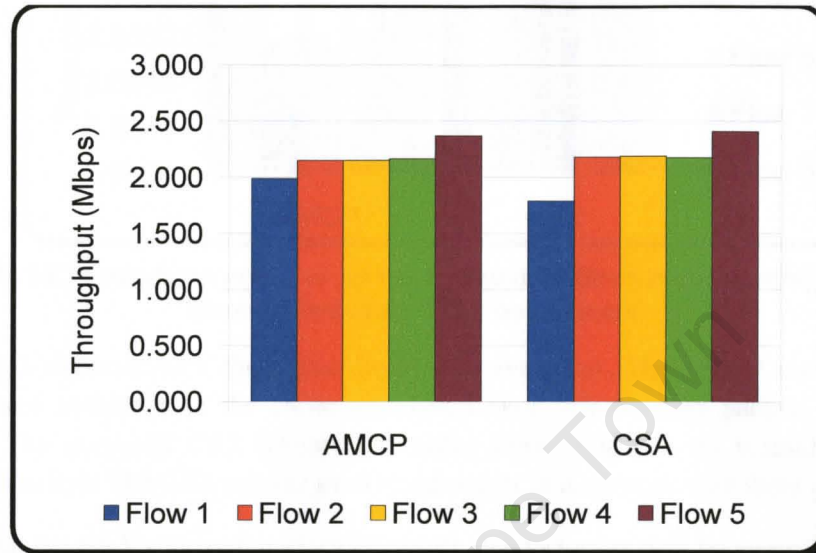


Figure 6. 13. The performance of a system with five data flows implementing both channel switching delay schemes.

We also evaluated the proposed approach in a network with fifteen data flows in Fig 6.14. We sought to create a notion of highly congested and backlogged network. A similar pattern to Figs 6.11 and 6.13 was also observed in Fig 6.14 though with some variations. The first data flow is still a challenge in larger networks. Interestingly, the overall achieved throughput is more than the achieved throughput in Fig 6.13 and it also compares favourable with Fig 6.11. This shows that interference caused by the number of data flows was not an issue as it was in Fig 6.13. The high incidence of interference in Fig 6.13 was largely caused by an interfering data flow. There was one more data flow than the data channels. In this case, spatial reuse has taken care of this challenge.

The network in Fig 6.14 was three times bigger than the one in Fig 6.13. Fig 6.14 achieved better throughput despite the size of the network. This confirms the argument that the proposed scheme is more scalable and it does improve with network size. Data channels are degraded by longer data packets, the MSC, and the double effect of channel switching delay. The capacity of the control channel is, on the other hand, improved by the degradation of data channels. Spatial reuse of both control and data channels coupled with the degradation of data channels by both data packets and two channel switching delay durations improves the performance of our scheme in large networks.

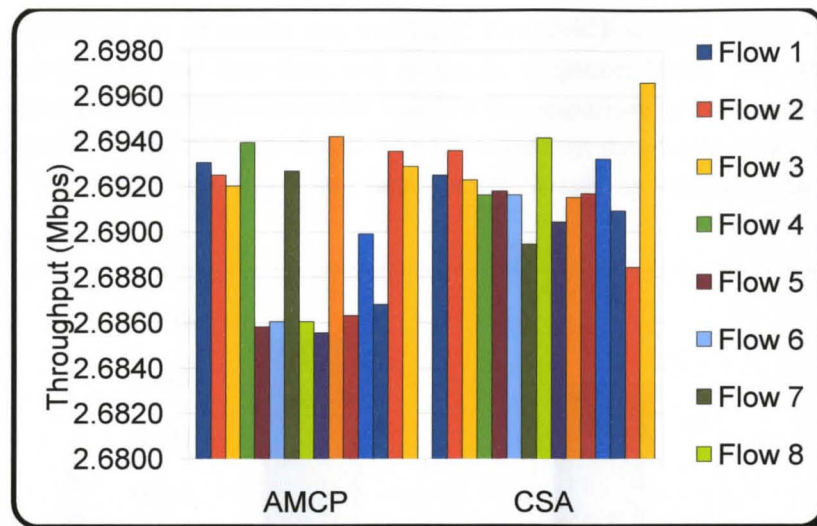


Figure 6. 14. Throughput achieved by the fifteen data flows implementing the two channel switching delay approaches

In Fig 6.15, a network with three data flows was evaluated. The AMCP scheme did not experience any collisions in the entire simulation time. All the sent packets were safely delivered. The proposed CSA scheme did suffer from collisions, as a result significant throughput was lost. The CSA scheme performed poorly in a network with three data flows.

We noted that the CSA approach performed poorly due to longer data transmission durations owing to the addition of two channel switching durations. It therefore suffered longer waiting durations in small networks. The poor performance of the scheme in smaller networks shows that there is no performance benefit of the proposed scheme in small networks. However, as the network load increased, the scheme performed better. The capacity of the control channel improved under heavy loads and performed better. This property lends itself to network scalability.

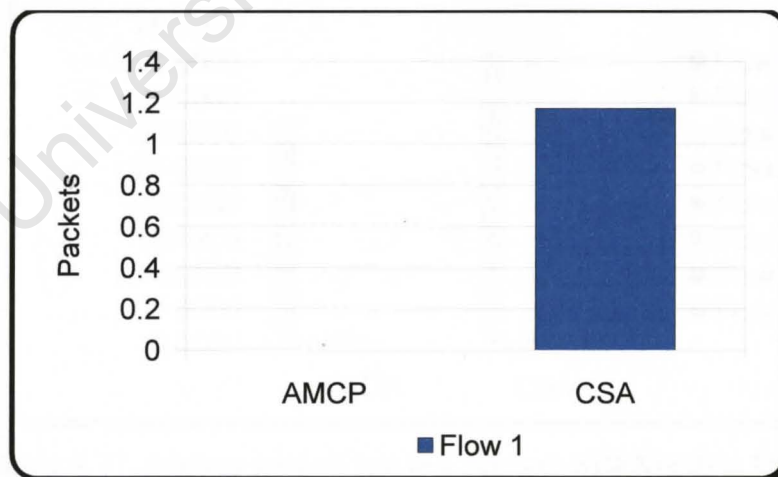


Figure 6. 15. Average packet losses in a network with three data flows.

In Fig 6.16, a different set of results was obtained. The AMCP scheme began experiencing some losses; though only one data flow was subjected to packet losses. The AMCP losses were more severe and significant bandwidth was lost in comparison to the losses experienced by the CSA scheme for the two data flows. The CSA had two data flows which experienced packet losses, but it did experience less data packets losses as compared to the AMCP scheme.

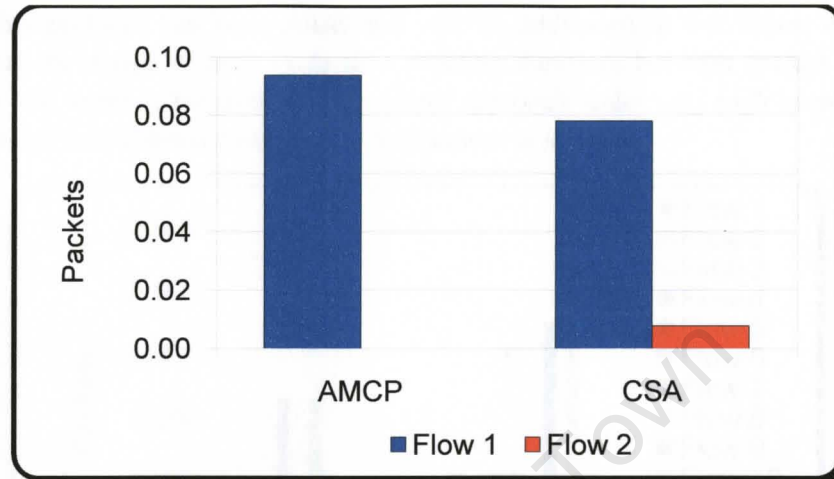


Figure 6. 16. Average packets lost in a network with four data flows.

In Fig 6.16 the number of data flows was increased to 4 and other parameters were unchanged. However, there were no losses in other data flows, as can be seen in the results, an additional data flow caused significant losses in flow 1 of the AMCP scheme. In the CSA scheme, though a second data flow was also affected, it lost fewer packets than AMCP scheme. The increase in data flows therefore did not cause significant losses to the CSA. In Fig 6.17, the size of the network was increased to 10 nodes with 5 data flows.

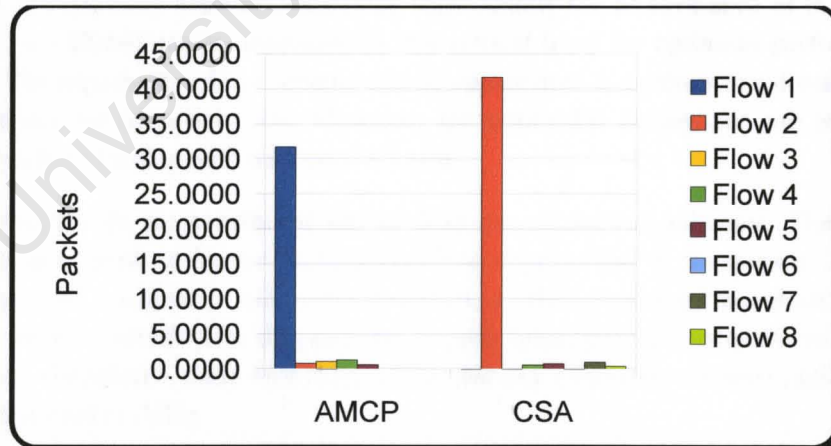


Figure 6. 17. Average packets lost in a network with five data flows.

In Fig 6.17, it was noted that the AMCP technique suffered the worst performance in the first data flow, whereas the worst performance of the CSA scheme was noted in the second data flow. For the other data flows, the performance of the CSA scheme was better than the AMCP

scheme. However, wastage in bandwidth was minimal for the rest of the data flows for the two schemes. The increase in the network size had a negative effect on the performance of the two approaches in terms of lost packets.

In heavily loaded networks, the CSA scheme's performance was very poor in terms of wasted bandwidth. In Fig 6.18, a network with thirty terminals was considered. The CSA scheme recorded significant packet losses in most of the data flows in comparison with AMCP approach. This problem has been noted and will be addressed in our future work. It is envisaged that the design of inter cycle time (waiting durations between cycles) will solve this problem and improve the performance of our approach under very high network loads. However, for end to end throughput, the CSA scheme was superior.

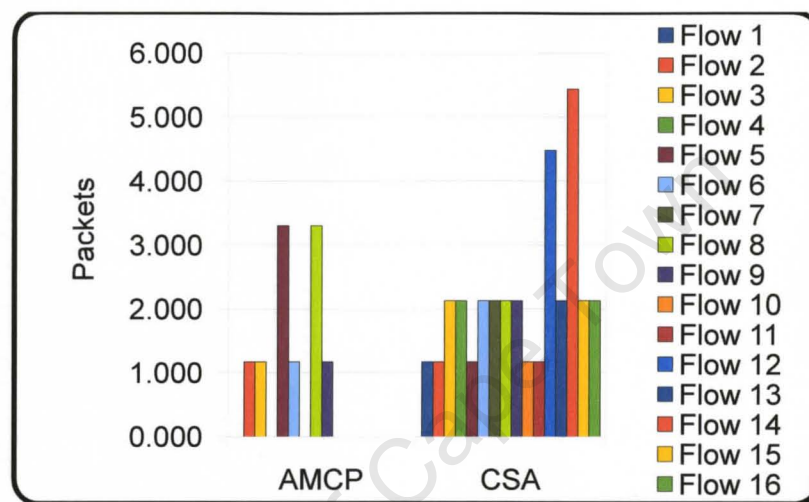


Figure 6. 18. Average packet lost in a network with fifteen data flows.

It should be noted that though the performance of the control channel improves with the network size, it eventually saturates degrading significantly the performance of the network. The network size should not be increased to this critical level for optimum performance of the network. The superiority of our scheme can be appreciated in medium sized networks and will be optimized for large networks. However, for achievable throughput and packet drop rate, the CSA scheme scales well with network size.

In the following results we considered packet drop rate of the two schemes. These packets were dropped as a result of longer waiting durations experienced in the queues. They were dropped because of congestion and buffer overflow, as the queue limit has been exceeded. There are no packets which were dropped due to path breakages and unreachable receivers. The simulation considered static terminals which did not experience broken paths and lost paths due to terminal mobility.

In Fig 6.19, the performance of the proposed CSA scheme was evaluated in a network with 3 data flows. Its performance was evaluated in terms of the rate at which packets were dropped (packet drop rate).

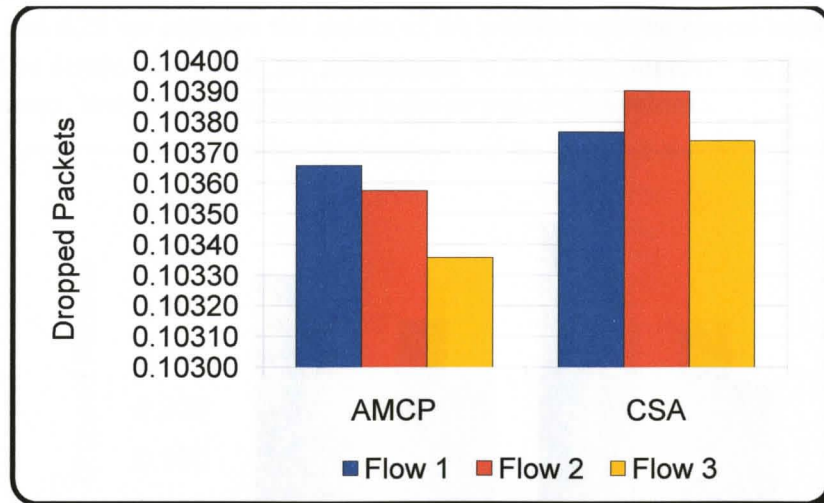


Figure 6. 19 Dropped packets in a network with three data flows

The CSA scheme experienced a higher incidence of dropped packets in all the three data flows. The AMCP scheme recorded fewer losses. The superiority of AMCP scheme is related to the size of the network and the fact that the CSA scheme has longer data transmission. The CSA scheme performed poorly in small network. Its performance improved as the network grew in size as evidenced in Fig 6.20 which shows an improvement in the CSA scheme.

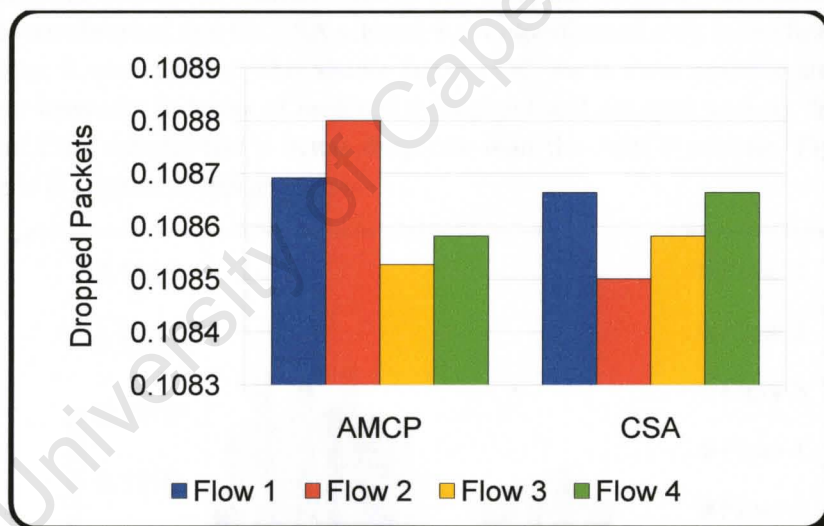


Figure 6. 20. Dropped packets in a network with four data flows

In Fig 6.20, the size of the network was increased to four data flows sharing the 4 available data channels. The AMCP scheme performed better in the third and fourth data flows. It dropped fewer data packets. The CSA scheme was superior in the first and second data flows. In overall, the CSA scheme performed better than the AMCP scheme. The performance of the CSA scheme improved with the increase in the size of the network.

In Figs 6.21 and 6.22 we compare the results of the smallest and the largest networks in our simulation. The results show how the performance of the CSA improves as the size of the network increases. They show how scalable is the proposed CSA scheme.

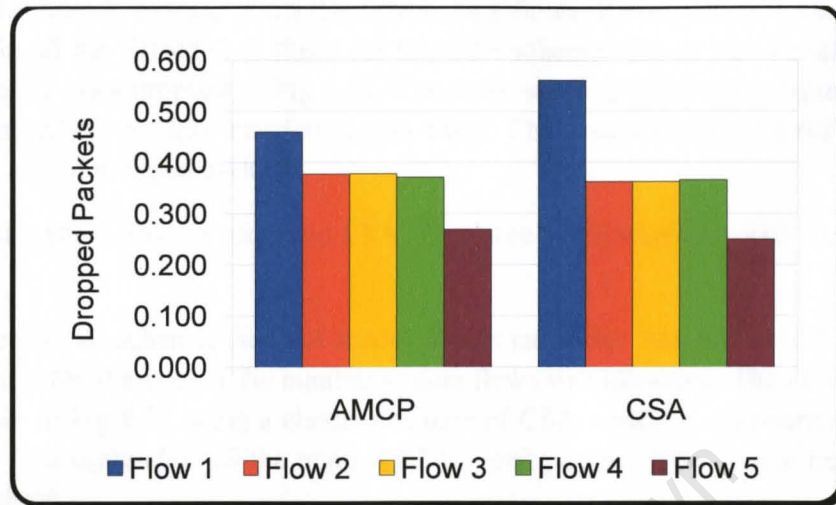


Figure 6. 21. Dropped packets in a network with five data flows

In Fig 6.21, it becomes more apparent that the performance of the CSA scheme improves with the increase in the size of the network. In Fig 6.21, the network was increased to five data flows. It was observed that the CSA scheme was outperformed only in the first data flow. For the last four, it was superior. This shows that the DC_sw is more scalable and performs better in larger networks in terms of received throughput and dropped packets. In the last 4 data flows the CSA scheme had a better drop rate than the AMCP scheme. Fig 6.22 is a classic example in support of this argument.

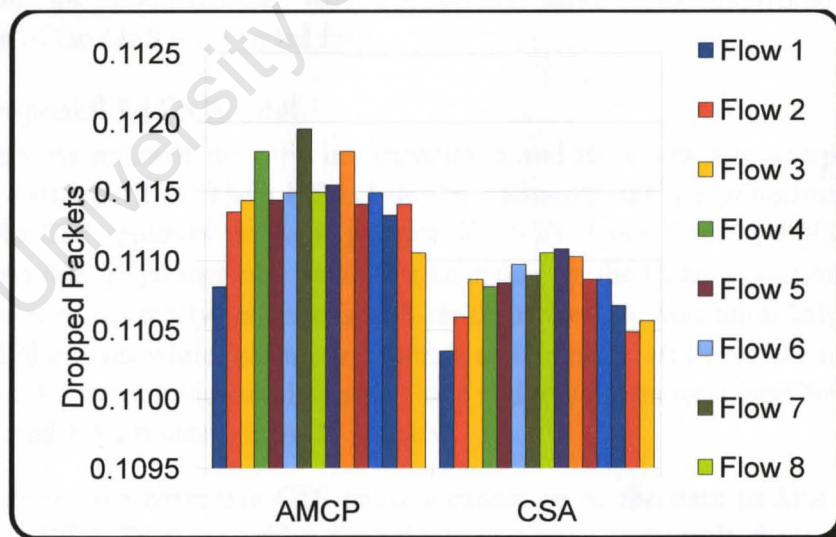


Figure 6. 22. Dropped packets in a network with fifteen data flows

In Fig 6.22 we increased the size of the network three fold to fifteen data flows. As expected, the performance of CSA scheme kept on improving as the network size grew. In this case, it outperformed the AMCP scheme in all the fifteen data flows. Fewer dropped data packets were recorded in all the fifteen data flows for the CSA scheme. The dropped packets were even fewer than the ones dropped in Fig 6.21. The more severe performance degradation in Fig 6.21 was caused by the fifty interfering data flow. This explains why Fig 6.21 has the highest average rate of dropped packets.

The results clearly show that our proposed CSA is scalable and it improves with the increase in network size.

The performance of our scheme, the CSA model performed better than the AMCP model. It outperformed the AMCP model as the number of data flows was increased. The network with fifteen data flows in Fig 6.22 being a classic example of CSA scheme's superiority over the AMCP scheme in consideration of the number of dropped packets. This is also true for the achieved throughput.

It was also noted that the increase in the number of data flows also degrades the performance of the network. The percentage of dropped packets increased steadily with the size of the network. The degradation caused by data flows is significant where there is an interfering data flow as show in Fig 6.21. The spatial reuse of data channels and the control channel minimizes the effects of interfering data flows.

In Section 6.4, the reconfiguration of the EIFS in both single and multi-channel MAC protocols is evaluated. In the single channel MAC protocols the EIFS was replaced with the LIFS, while in the multi-channel MAC protocols, CIFS was implemented. The implemenation of the LIFS is discussed first.

6.5 THE Proposed LIFS Model

We discuss briefly the rationale the LIFS implementation and show how it was implemented along with the existing EIFS. The LIFS scheme is optimized for the protection of data packets while the EIFS protects the ACK packets. Fig 6.23 shows how the EIFS protects ACK packets and fails to protect data packets at reception. In the Communication Sensing Zone (CSZ), nodes which receive erroneous RTS set their Network Allocation Value (NAV) to EIFS. The EIFS expires while data transmission is still ongoing. However, the nodes will continue to sense this transmission until its end. These nodes will then reset their NAV values to EIFS. The second EIFS protects the ACK packets.

The nodes which receive erroneous CTS packets cannot sense the data packets after the expiry of the first EIFS. They are hidden from the transmitters; as a result, these nodes can initiate communication while the current data transmission is still ongoing thereby destroying data packets at reception.

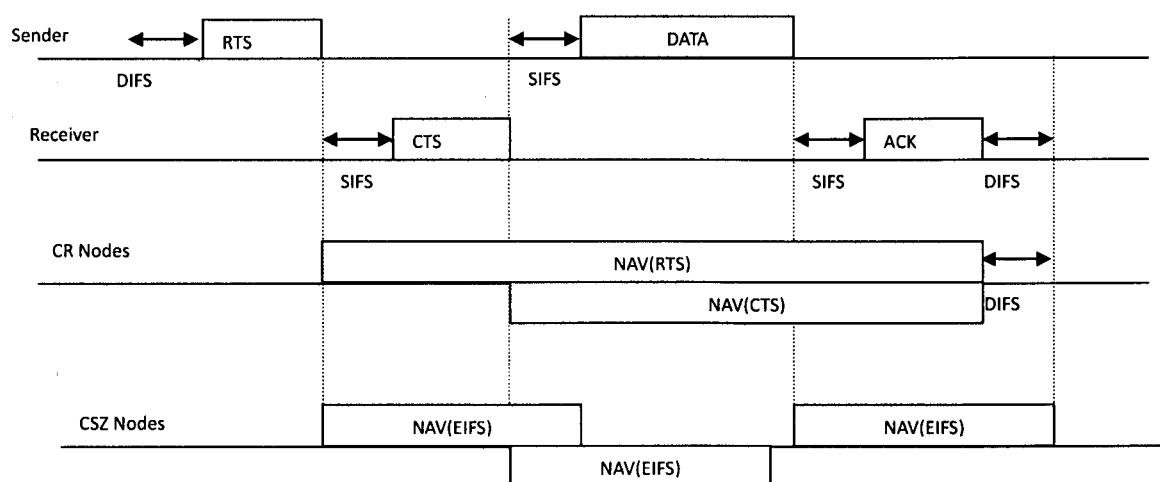


Figure 6. 23. EIFS Implementation

The RTS/CTS are only effective within the Communication Ranges (CR) of both the sender and receiver. Nodes which overhear a RTS or CTS set their NAV values to RTS or CTS duration, respectively. Effectively, terminals within the communication ranges of sender and a receiver will not initiate any communication during the ongoing transmission. These nodes are depicted as CR nodes in Fig 6.23. Unfortunately, the nodes in the Interference and Carrier Sensing ranges which are in the CSZ will overhear one of the two control packets but will fail to decode them. They will not know for how long they should defer their next transmissions.

To address these shortcomings an EIFS scheme was introduced. Nodes that receive erroneous RTS/CTS packets set their NAV values to EIFS. Considering CSZ nodes (Nodes within Interference and Carrier Sensing Ranges) in Fig.6.23, which are in the sender neighbourhood will set their NAV values to EIFS upon receiving erroneous RTS packets.

The EIFS duration expires before the end of data transmission. However the Physical layer (PHY) will sense the ongoing Data transmission until the end of data transmission. Thereafter, the listening nodes will reset their NAV values to EIFS duration. The second EIFS duration is depicted in Fig.6.23 under the CSZ nodes, clearly demonstrating the effectiveness of EIFS in the sender's neighbourhood, protecting effectively the ACK packets.

The EIFS is effective in protecting ACK packet reception. It is however not effective in protecting the DATA packets. When the EIFS duration for the nodes in the CSZ of a receiver expires, the nodes in this zone cannot sense the ongoing transmission from the sender. Nodes which are in the CSZ of the receiver and outside the transmitter's zone can start sending packets destroying DATA packets at the receiver. The proposed LIFS scheme addresses this shortcoming of the EIFS scheme. It protects both the reception of DATA and ACK packets.

In order to implement the LIFS protocol successfully, we first re-zoned transmission radii of the IEEE 802.11 MAC radio. We therefore consider two transmission ranges, CR and the CSZ. The CSZ integrates the interference and carrier sensing ranges into one zone depicted in Fig 6.24b. Erroneous packets are received in CSZ.

Erroneous packets differ in severity as one move further away from the CR. Closer to the CR; some packets may be received correctly. Unfortunately, if they are not decoded correctly they

are likely to cause interference. Given the detection mechanisms in [77], packets in this region can be detected in a similar way. To simplify processing complexity, all CSZ erroneous packets should be detected in a similar way.

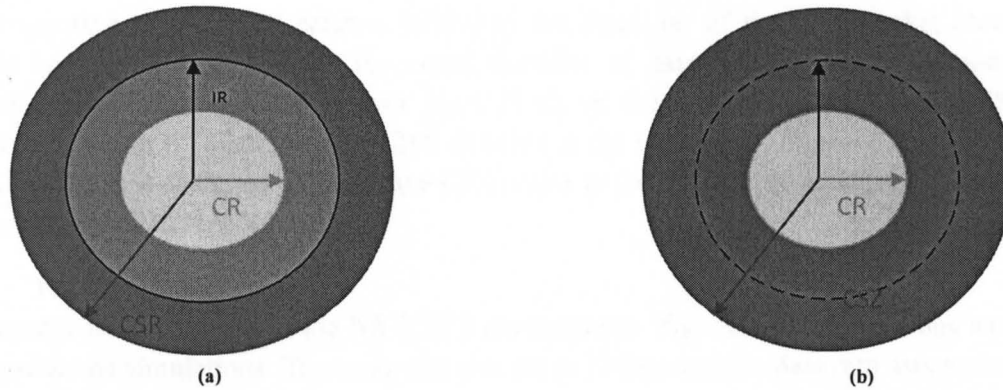


Figure 6. 24. Communication zones: (a) conventional model and (b) proposed model.

The implementation of the LIFS scheme depends on the detection of CTS packets. The scheme is CTS based and its execution is triggered once a CTS condition is met. The question arises as to how the detection of the CTS packet would be possible given the fact that the MAC is not able to decode the erroneous CTS packets. This challenge can be solved through the carrier sensing techniques. We combine the Physical Carrier Sensing (PCS) and the Virtual Carrier Sensing (VCS) techniques described in [77]. Furthermore, control packets are transmitted at a lower rate making their detection much easier.

When the Physical Layer Convergence Protocol (PLCP) header is transmitted at a lower rate, hence the packet can be interpreted through the PLCP header [77]. The length and the type of the control packet can therefore be ascertained. This is possible given the length and signal fields in the PLCP header. The RTS packet is longer than the CTS packet. The information contained in the header will be passed on to the MAC after the physical layer has interpreted it.

The PCS technique can be employed in observing the length of the packet heard on the medium. In this case, the difference in length of a RTS and CTS will help in identifying which packet is being heard on the medium. As a result the CTS packet can be observed which then triggers the execution of the LIFS protocol. Therefore, the difference in the transmission time of the control packets is a sufficient condition for the execution of the LIFS scheme. If the control packet cannot be detected in this way the following approach can be employed.

The Clear Channel Assessment (CCA) mechanism can record the duration the medium was sensed busy [77]. Once the duration of the activity on the medium has been ascertained, the information can be used to calculate the transmission time and therefore the length of the packet. The packet length will be valuable in the identification of the control packet which was heard on the medium.

The second form of detection is handy when the PLCP header is not correctly received [77]. However, in a simulated environment, unlike in the real world this challenge can be easily handled. The condition for CTS detection is met easily in a simulated environment.

The triggering of the LIFS scheme following the detection of the CTS packet blocks all would be hidden terminals for the entire duration of data transmission. Collisions will therefore be eliminated at the receiver. Fig 6.25 shows the implementation of the LIFS after the detection of a CTS packet. The LIFS duration is the summation of two SIFS, DATA and ACK packet. It is designed to inhibit the CSZ nodes in the CSZ of the receiver, the last block in Fig 6.25 labelled NAV (LIFS).

6.4.1 The simulation setup

The model was simulated in the NS 2.29.2 environment. The default NS 2 values were not changed in the simulations. The basic rate was set to 1Mbps and the data rate was assumed to be 1Mbps. Nodes were allowed to move from position x to $x + 1$ however, node mobility was not part of this project. Mobility was therefore not investigated and analyzed. The final state of the simulation scenario considered a static state of the nodes.

Ad hoc On-Demand Distance Vector (AODV), Destination-Sequenced Distance Vector (DSDV), Dynamic Source Routing (DSR) and Dumb Agent routing were considered. The simulation was run at least ten times with each run lasting for three hundred seconds of simulation time. A TCP traffic agent was attached to each sending node.

Our simulation scenario had a total of fourteen nodes with a common starting point. Nodes move in a flat grid of 550 by 1550 metres into different positions forming a chain like topology. Nodes move from their initial positions to new positions and remain static in these new positions for the entire simulation. Nodes start communication once they had moved into their new positions. The chain-like topology helps to investigate control packets handshake, interference and the implementation of the LIFS scheme in a more controlled manner. It also helps in reducing routing related overhead costs. Nodes start communicating after the formation of the chain-topology. Therefore, node mobility in this case was not applicable.

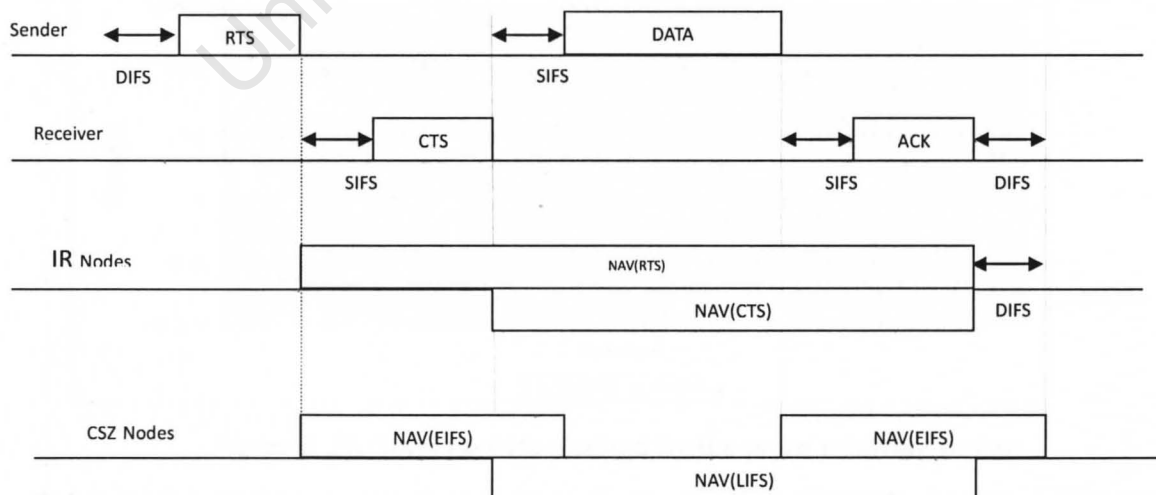


Figure 6. 25. LIFS Implementation

The chain-like topology was chosen to study the Hidden node problem. It was also employed to ensure fair comparison of this scheme to other schemes. Most protocols consider a chain-like topology. Each node was placed within the communication range of the next node.

The nodes were organized into transmitter-receiver pairs with seven transmitters and seven receiving nodes. The transmitters start sending data at the same time and end at the same time. The chosen packet generation rate results in the worst case scenario of a backlogged network. Numerous collision states were created to investigate the efficiency of the scheme. Each transmitter sent packets continuously during the simulation time. Given the dynamic routing algorithms implemented in the simulation, some communicating pairs failed to establish routing paths for the entire simulation time. Packets for the affected nodes were dropped.

6.4.2 Performance Evaluation

The simulation data was first recorded into trace files, thereafter relevant elements and data of interest was extracted into separate files, using the AWK programming language. The extracted data was also exported into the MS Excel® environment for representation. Data was classified and represented in graphical forms. However, Linux shell programming tools were used for the major part of the data analysis.

In general, there was a lot of unfairness in throughput allocation as can be seen in the results in Fig 6.26. Some of the nodes were not able to send or receive a single packet. This was caused by dynamic routing protocols employed in the simulator. The dynamic routing problem was studied and highlighted in [78]. Work in [77] also previews this problem. However, LIFS exhibits a measure of fairness for the middle nodes though it does not address this unfairness. The fairness of LIFS can be improved by using non dynamic routing protocols.

The improvement in throughput fairness was observed when default NS 2.29.2 data rates of 1Mbps were implemented. However the scheme was not investigated with higher data rates. Improvement in end-to-end throughput is also anticipated when a precise LIFS length is designed. However, the small improvement shows that LIFS approach is effective.

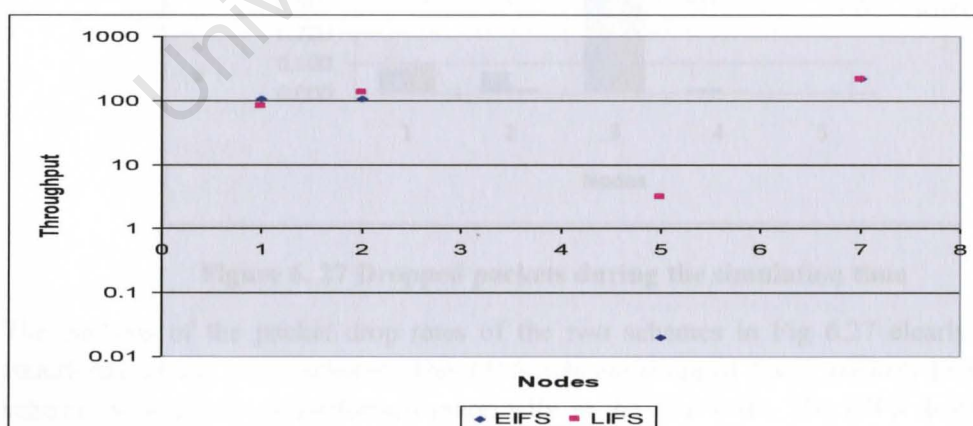


Figure 6. 26. Total packets received by the seven receiving nodes.

In Fig 6.26, fairness in throughput distribution in the LIFS scheme can be noted in the middle nodes, for example the second and the fifth nodes achieved better throughput. However, the performance of the LIFS scheme was not that good for the first and the last nodes. It was outperformed by EIFS in the first and the last nodes, though the difference is marginal. In the middle nodes its performance is encouraging and it performed better than EIFS.

The first and the last node in the chain-like topology have the highest throughput because they suffer the less amount of interference. The other nodes have all the four packets vulnerable whereas the first and the last nodes have two of the four packets which are affected. Interestingly, the last node had the higher bandwidth than the first. The RTS and the DATA packets of the last node were not vulnerable while for the first node they were vulnerable. The ACK and the CTS packets of the last node were affected instead and these are smaller in size as compared to DATA and RTS packets. This explains the highest throughput obtained by the last node in Fig 6.26. Furthermore the success of an RTS packet improves channel reservation chances of a node, hence the better achieved throughput.

The RTS initiates communication and reserves the channel, hence its destruction degrades throughput significantly. The performance of LIFS in the last node closely matches EIFS, while in the first node, it was outperformed. The closeness of the two schemes in the last node shows the effectiveness of LIFS in protecting data packets. The main objective of LIFS is to protect data packets. The distribution of bandwidth also shows the unfairness of the IEEE 802.11 MAC standard. These two results depict a worse case of unfairness caused by the implementation of dynamic routing protocols. A number of middle nodes fail to establish routes due to dynamic routing protocols which were implemented. In Fig 6.27 the packet drop rate of the LIFS is evaluated.

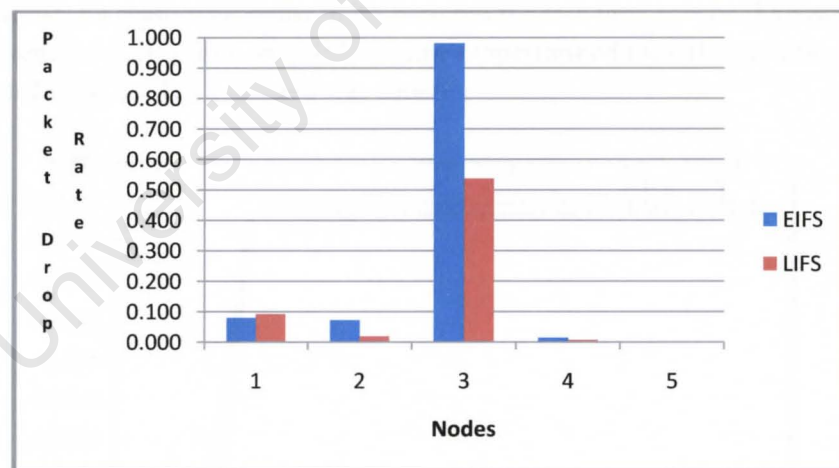


Figure 6. 27 Dropped packets during the simulation time

The analysis of the packet drop rates of the two schemes in Fig 6.27 clearly shows the superiority of the LIFS scheme. The LIFS scheme dropped fewer packets than the EIFS scheme. It was only outperformed marginally in the first node. The EIFS dropped almost hundred percent of the packets generated by the third node while the LIFS dropped nearly

half of the packets dropped by the EIFS scheme. This clearly shows the superiority of the LIFS scheme.

In Fig 6.28 we tagged the first data flow and analyzed its end-to-end delay for the two schemes. We observed that the end-to-end delay of the LIFS was lower than that of the EIFS scheme in all the cases. The initial value of the LIFS's delay was lower than the one for the EIFS scheme. When both schemes reached their saturation levels, their delays thereafter became constant as the network was overloaded. However, the delay for the LIFS for a saturated network scenario was less than of the EIFS.

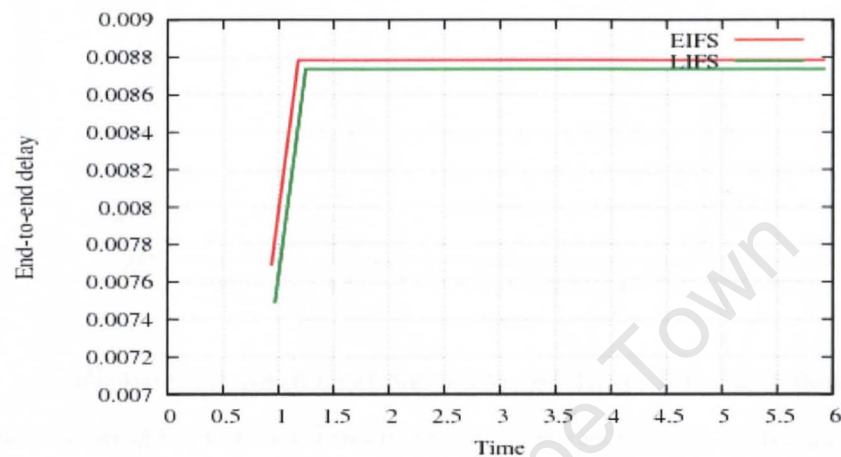


Figure 6. 28. Analysis of the end to end delay of the first flow

We also analyzed the two schemes' second data flows in Fig 6.29. It was noted that the EIFS scheme experienced a reasonable better delay between 0.5 to 1 time epochs. Thereafter, as the two schemes reached their peaks, the LIFS scheme outperformed the EIFS scheme. However, for the saturated state, the LIFS scheme was superior

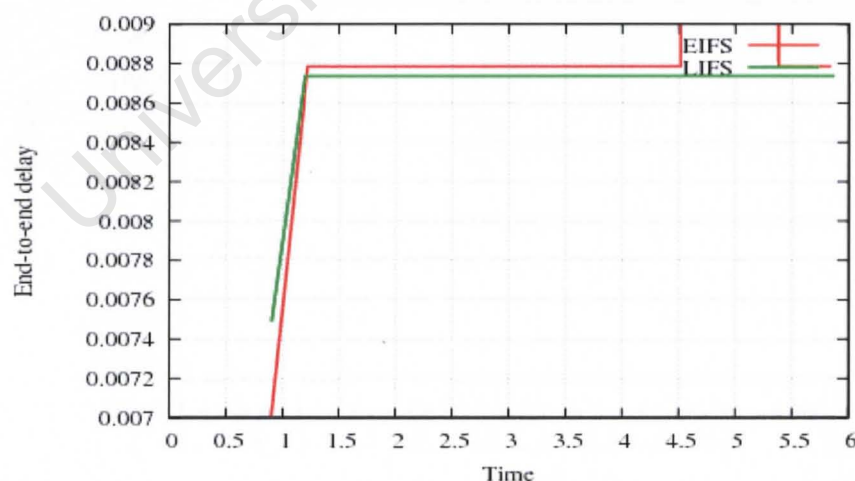


Figure 6. 29. Analysis of the end to end delay of the third flow.

For the third flow depicted in Fig 6.30, the LIFS scheme was clearly superior. It began experiencing delays towards the end of the simulation while the EIFS was subjected to some delays at the very beginning of the simulation. Furthermore, the proposed scheme's saturation point was better than that of the EIFS scheme.

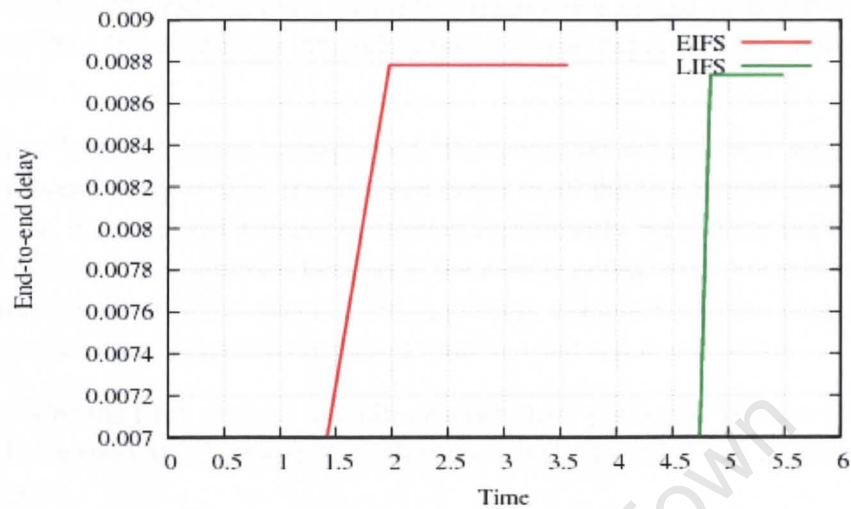


Figure 6. 30. Analysis of the end to end delay of the third flow

Lastly, we evaluated the last data flows of the two schemes in Fig 6.31. It was also noted that the proposed scheme offered better performance than the EIFS scheme. For the entire simulation time its end-to-end delay was superior. However, between 1 and 1.5 time epochs the proposed scheme was marginally better than the EIFS scheme. We therefore conclude that the proposed scheme is superior and it does offer better network performance.

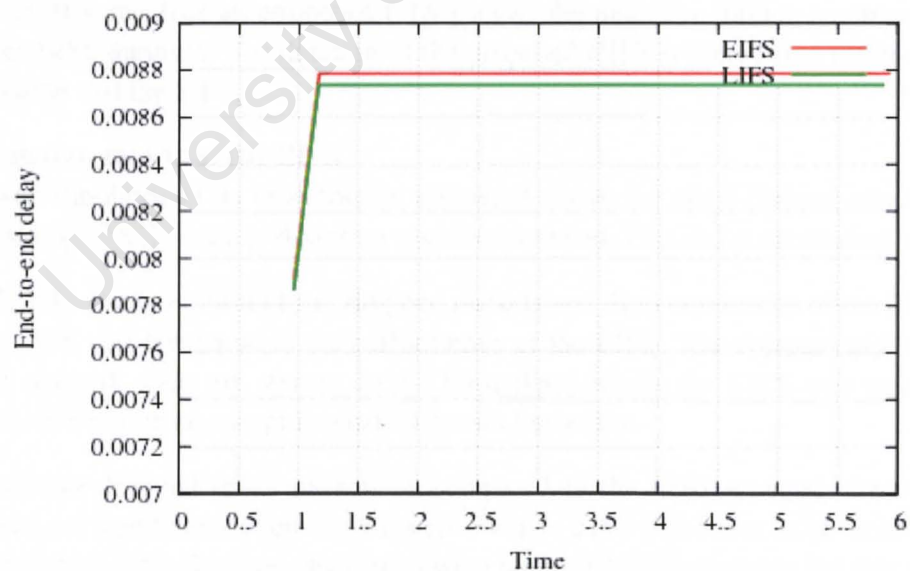


Figure 6. 31 Analysis of the end to end delay of the fourth flow

The performance of LIFS can be improved by identifying nodes which are in the capture region. Nodes which are at the edge of the transmitter's communication range are most likely to be in the capture region. A number of packets in this region can be delivered successfully. This may result in the improvement of LIFS' performance in end to end throughput. The superiority of the LIFS scheme in the middle nodes is also expected to be more pronounced and significant.

LIFS performs better in queue management. The proposed scheme was superior over the EIFS in end-to-end delay results. It performed better in all the four tagged data flows. In the third data flow, the proposed scheme performed significantly better than the EIFS scheme. This shows that the LIFS improves fairness in the middle nodes which are otherwise affected by the highest amount of interference. LIFS in general, exhibited a higher degree of fairness in bandwidth allocation, superiority in packet drop rate and end to end delay.

We then extended the LIFS concept to multi-channel MAC protocols. The new IFS version of LIFS in multi-channel MAC protocols is called the CIFS. The CIFS was implemented on the control channel.

6.6 The implementation of CIFS

The implementation of the CIFS scheme is the extension of the LIFS. The CIFS inter-frame scheme was implemented on the control channel. The CIFS scheme is designed to force a node receiving an erroneous packet on the control channel to defer for a shorter duration as compared to the EIFS duration.

A node which receives an erroneous RTS packet has to defer for a summation of CTS and SIFS duration. If it receives an erroneous CTS packet, the node can initiate communication soon after the SIFS duration. The duration of the proposed CIFS is therefore a summation of the CTS duration and the SIFS.

6.5.1 Simulation results of the CIFS

The CIFS was simulated in an environment discussed above for multi-channel simulations. The No Ad Hoc (NOAH) routing algorithm was implemented. This is a static routing agent.

In Figs 6.32, 6.33 and 6.34 throughput, dropped packets and drop rate results of the CIFS are shown. The CIFS was compared to the performance of the EIFS. The average results of the six different network sizes are shown. In the throughput results the CIFS was marginally better than the EIFS scheme except in a network with ten nodes.

The CIFS scheme dropped fewer packets as compared to the EIFS scheme; however, the difference was not significant. There is an instance where EIFS was better as observed in the throughput results. Lastly, the drop rate results were more or less the same as the first two set of results. The CIFS performed better in all cases.

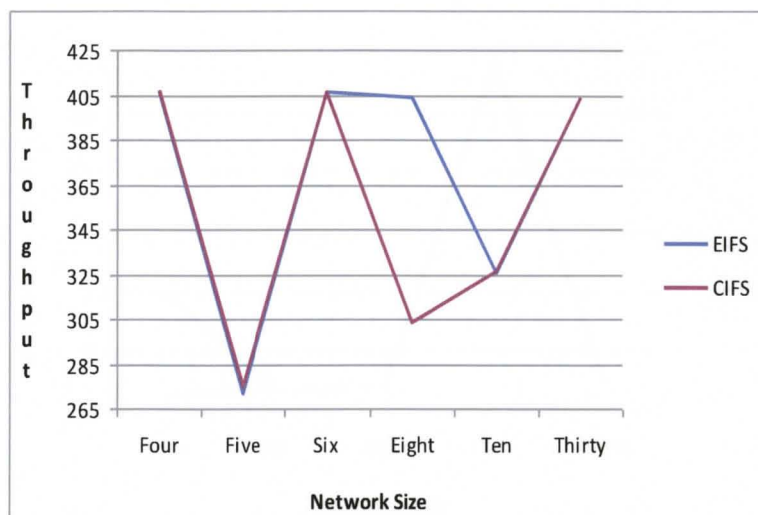


Figure 6. 32. The achieved average throughput by the six different networks

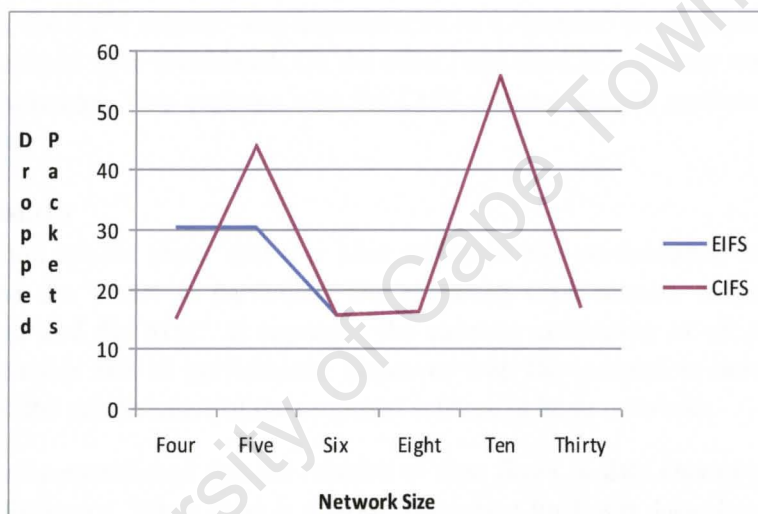


Figure 6. 33. The average number of dropped packets by the six networks

The CIFS duration is a very small duration hence the small impact it exhibited. Its benefit is likely to be significant in large scale networks. Secondly, the simulation scenarios which were considered did not give perfect conditions for the CIFS to achieve the expected best results. There were no significant congestions in the network and the collisions were very few. The number of data channels which were employed offered all the nodes a fair amount of time to transmit. As a result, the worst case of the EIFS in large scale networks was not tested adequately. However, the small improvement which was realized is an indication that CIFS is worth consideration. The result of the LIFS scheme in single channel MAC protocols showed the necessity of these reconfigurations of the EIFS scheme. The LIFS scheme was good in reducing end-to-end delay and this tie well with the CIFS scheme results. For example, the EIFS was better in all the networks when the drop rate metric was considered.

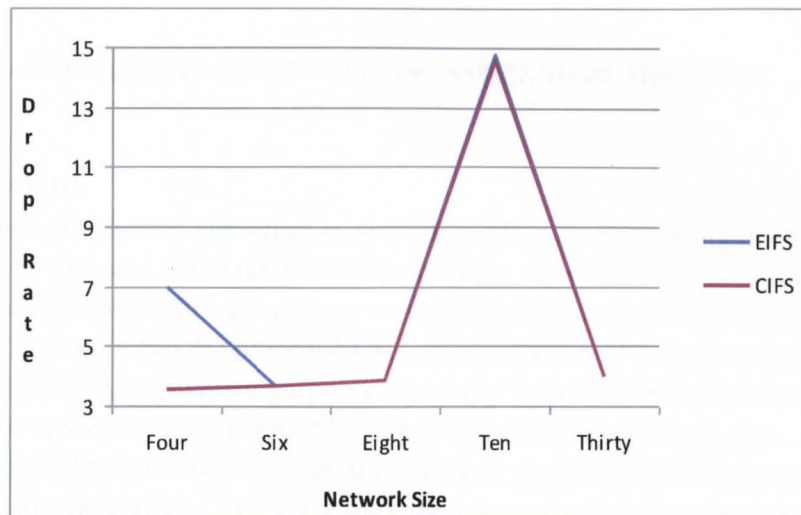


Figure 6. 34. The average drop rate of the six networks

Furthermore, the LIFS scheme was implemented in a dynamic environment where dynamic routing algorithms were considered. On the other hand the CIFS scheme was implemented in a static environment. This explains why the CIFS scheme did not perform at a level of the LIFS scheme.

6.7 Summary

The simulation results show that our idea improves the performance of wireless access networks and the WMN in particular. The proposed CSA scheme reduces the signalling overhead cost and the MSC. It improves the capacity utilization of all the channels. The scheme is scalable and its performance improves with the increase in network size. This is evidenced by the performance of the proposed scheme in large networks.

The project also established that the relation of data flows to data channels has an effect on network performance. When there is a lot of contention for fewer data channels, interference increases. The interference caused by an interfering data flow is more severe than the degradation caused by an increase in network size. However, when the number of the data channels is equal to the number of data flows, network performance is also affected and the degradation of the network is significant. When the number of data flows and data channels is equal, an additional data channel improves the performance of the network. The paper concludes that spatial reuse and the degradation of data channels improve the performance of the CSA scheme as the number of data flows is increased.

Chapter 7 - Virtual orthogonal channel assignment algorithm

7.0 Introduction

A virtual channel assignment algorithm is proposed. The algorithm assigns channels in an orthogonal way to increase the number of data channels. Most existing multi-channel MAC protocols assume that the multi-channels are orthogonal. This research also assumed that the channels are orthogonal when the proposed CSA was evaluated. However, the research made such an assumption for investigative purposes especially to understand whether there is merit in increasing the number of channels. The conducted investigations confirm that there is value in using multiple channels. However, the available multi-channels are overlapping, and cannot all be used concurrently. There are only three non-overlapping channels [30], which cannot be used for effective communication. The number of channels should be more than three if any meaningful performance benefits can be derived. Given the fact that the available multi-channels are overlapping, this chapter explores techniques which can increase the number of orthogonal channels. Increasing orthogonal channels improves the performance of multi-channels.

This chapter proposes a virtual channel assignment algorithm, which increases the number of orthogonal data channel at use. The data channels are selected and assigned to transmitting pairs in an orthogonal way. A channel with enough separation from the previous channel is selected and assigned to the next pair. Virtual means that the protocol determines and selects a perfect orthogonal channel from the one which is currently in use. It does not use a frequency guard band approach but a predetermined channel selection and channel assignment strategy which ensures that a perfect orthogonal channel is used at any given time. The algorithm is implemented and evaluated in C++. The theoretical results of the proposed scheme are compared to the theoretical results of random and sequential channel assignment algorithms.

7.1 The significance of the channel assignment algorithm

The algorithm increases the number of orthogonal channels. It uses overlapping channels in a non-overlapping manner by assigning overlapping data channels to nodes to improve the aggregated capacity of the network and its performance. It ensures that the multi-channel protocols function at an optimum level.

The implementation of a dedicated control channel wastes bandwidth when there are a few data channels. The control channel improves network performance when many data channels have been added. The analysis of this research in Chapter 5 showed that the optimum number of data channels should be about eight.

7.2 Protocol description

In this section, we describe the proposed virtual orthogonal channel assignment algorithm (VORCAAL). The protocol description centres on the functionality of the channel assignment algorithm. Figure 7.1 shows the steps of the algorithm. It is a flow chart, which

abstract the proposed algorithm. The VORCAAL is a module which has to be integrated with the proposed cyclic scheduling algorithm. However, in this section it is treated as a separate entity to analyze its performance and behaviour under different conditions. We implemented and evaluated it as a self contained entity.

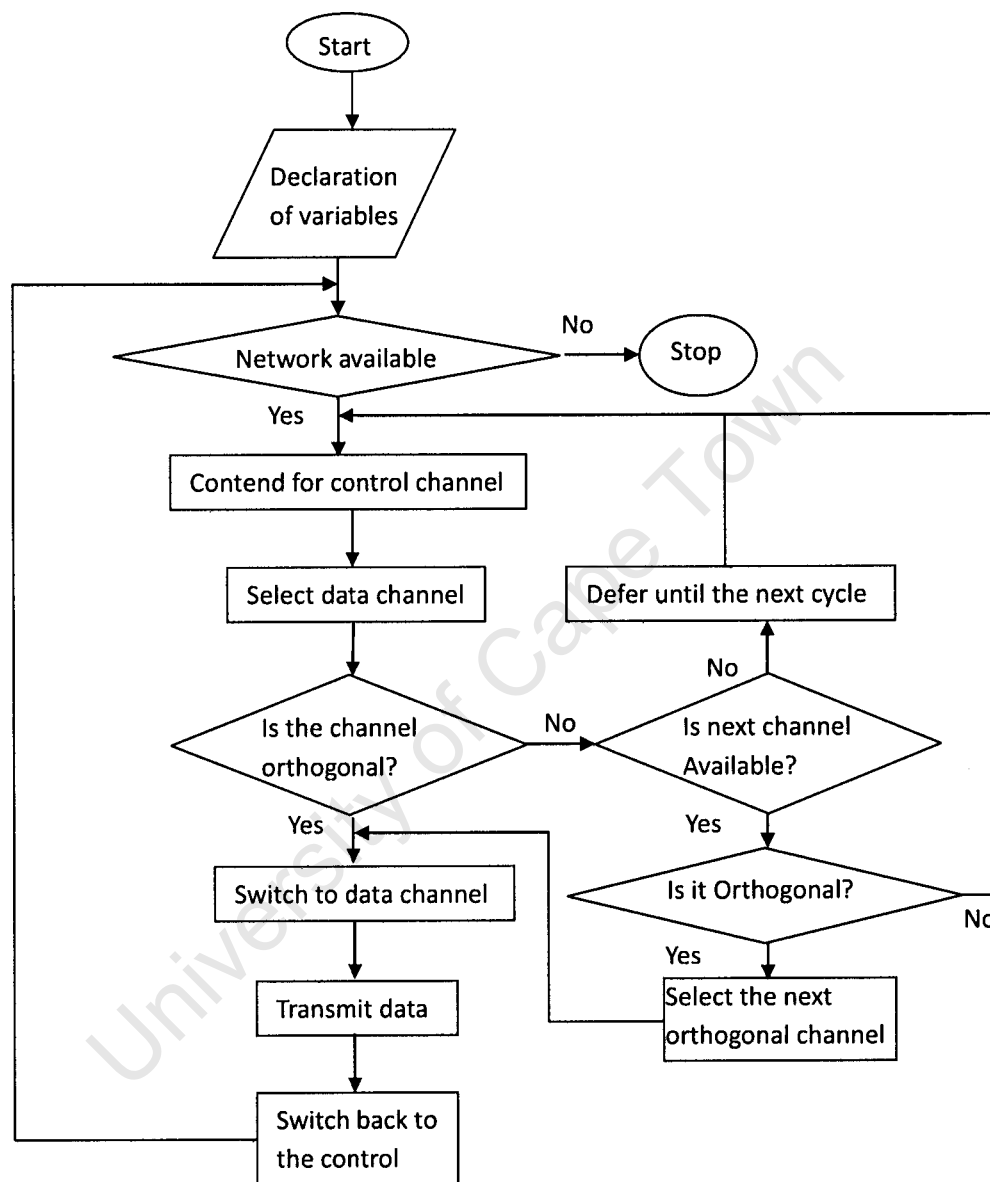


Figure 7. 1. The Virtual orthogonal channel assignment algorithm (VORCAAL)

The VORCAAL module first declares a list of variables which are required for its functional operation. It then enters into a loop to execute a series of instructions. In the loop, it first checks whether the network is available. If it is not available, it breaks out of the loop and execute program **stop** command to terminate execution. The **stop** command is not permanent, a node can retry later after random waiting time duration. If the network is available, execution enters into contention phase. The nodes contend for access to the control channel. Then the communicating pair reserves the next available orthogonal data channel. A decision

has to be made whether the selected data channel is orthogonal to the one which is currently in use. If the separation is not enough to ensure orthogonality, the nodes select the next possible orthogonal data channel; otherwise the nodes defer their transmission until the next cycle.

When the first decision evaluates to a true value, which confirms orthogonality, nodes switch onto the selected data channel. If there is a need to select a different data channel, execution branches to the next decision and checks for the availability of a free data channel. The available data channel is then evaluated in the third decision level whether it is orthogonal in respect to the one in use. If it passes this test, nodes then switch onto the selected data channel.

When the nodes have switched onto the data channel they exchange the data and the ACK packets before switching back onto the control channel. Nodes only switch back onto the control channel after the completion of the data transmission and sent packets have been acknowledged positively. Once the nodes have switched back to the control channel, the next cycle begins. Within a given cycle, a number of data transmissions are scheduled and more data channels are reserved. For brevity and ease of understanding, we trace a single flow through a single cycle; otherwise many flows can run through a single cycle more or less concurrently.

The following list of instructions explains further how the VORCAAL algorithms functions:

1. Declare variables
2. Initialize the variables
3. Check first whether the network is available
4. If it is not, abort otherwise continue
5. Contend for the control channel
6. Select a data channel
7. Check whether it is orthogonal to the previous channel
8. If it is, proceed to 12, otherwise check whether there is another available data channel
9. If not defer and go back to 5, otherwise select the next channel
10. Check whether it is orthogonal
11. If it is not orthogonal abort and go back to 5, otherwise proceed
12. Select the data channel
13. Switch onto the data channel
14. Transmit data
15. Switch back to the control channel or go back to 3.

7.3 The performance of the proposed algorithm

The VORCAAL algorithm was implemented in C++ and compared to other algorithms such as the sequential and random algorithms. The sequential algorithm assigns data channels to communication pairs sequentially, while the random algorithms generates and selects data

channels randomly. When the data channel has been selected in both sequential and random schemes, it is tested whether it is orthogonal to the previously selected data channel. If it is not, the data channel is not assigned to the communicating pair and the execution is aborted. The pair can make a second attempt to reserve an orthogonal channel or a different pair can do so.

The VORCAAL selects and assigns orthogonal data channels. It uses a pre-defined orthogonal pattern and assigns data channels to nodes according to the established list and pattern of orthogonal channels.

The three algorithms were all implemented in C++ and executed for the same number of cycles. In each cycle, there were 6 phases or time slots. Communicating pairs attempt to reserve one of the available data channels during each of the 6 time slots. Six virtual orthogonal channels are assumed. Eight different runs were considered. The first run had 10 cycles and the last run had a million cycles. A phase or a time slot refers to a single channel reservation attempt and it is assumed that a complete cycle has six possible channels which can be reserved. We also use run to mean cycle. The runs are the number of program interactions or the total number the cycles which were repeated.

We consider the maximum number of successful reservations and failed attempts in a cycle to analyze the proposed protocol. We compare the overall success rate as well as the average success rates of the three algorithms. We also analyze the failure rates of the three algorithms. In Fig 7.2 we considered the overall success rates of the three algorithms in the eight runs.

The VORCAAL was superior in all the eight runs. It outperformed both the random and the sequential algorithms because it utilizes all its time slots. The random algorithm was the second best. The sequential algorithm had the worst overall success rate in all the cases. The sequential algorithm wastes a number of time slots as it attempts to assign overlapping channels sequentially. The random algorithm wastes less time slots and its success rate is better than the sequential algorithm. The random algorithm assigns more orthogonal data channels than the sequential algorithm.

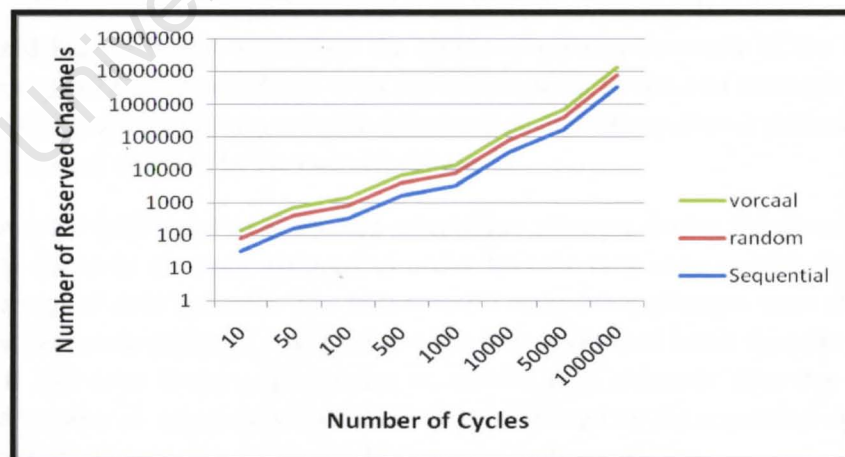


Figure 7. 2. Total number of successful reservation attempts

In Fig 7.3 below, the average performance of the three algorithms was considered. The overall performance was divided by the number of cycles for a given run to get an average performance of each cycle.

As can be seen in Fig 7.3, the VORCAAL was superior in all the runs. The random algorithm was the second best with an average of about 4.8 success rate. The sequential algorithm was the worst with a rate of about 3.2.

The results show that the prior knowledge of orthogonal channels is fundamental to improving the performance of multi-channel algorithms. The network should therefore be equipped with intelligence to facilitate the reservation of orthogonal data channels ahead of time. Instead of widening the frequency guard bands to ensure that channels are orthogonal at the same time reducing drastically the number of channels, approaches such as the VORCAAL will ensure that all the available channels are assigned and used in an orthogonal way.

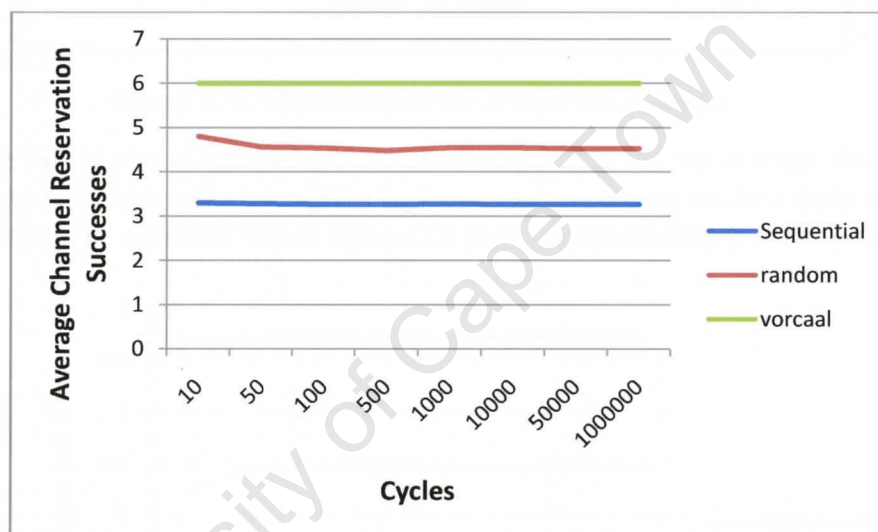


Figure 7. 3. The average number of successful attempts per a cycle

In Fig 7.4 and Fig 7.5 below we analyse the causes of poor performance of the sequential and random algorithms. The emphasis is on the unsuccessful reservation attempts of the two algorithms. We show how the sequential and the random algorithms did not perform well. We focus on the aborted attempts by the two algorithms.

Fig 7.4 shows the total number of aborted reservation attempts during the given runs. The selected data channels were not assigned to nodes because they were overlapping with the previously assigned data channels. The unsuccessful reservation attempts were aborted and marked as unsuccessful attempts. The random algorithm performed better than the sequential algorithm. It did miss fewer opportunities to reserve data channels than the sequential algorithm. A number of reservation opportunities were wasted by the sequential approach as it attempts to assign many data channels which are not orthogonal.

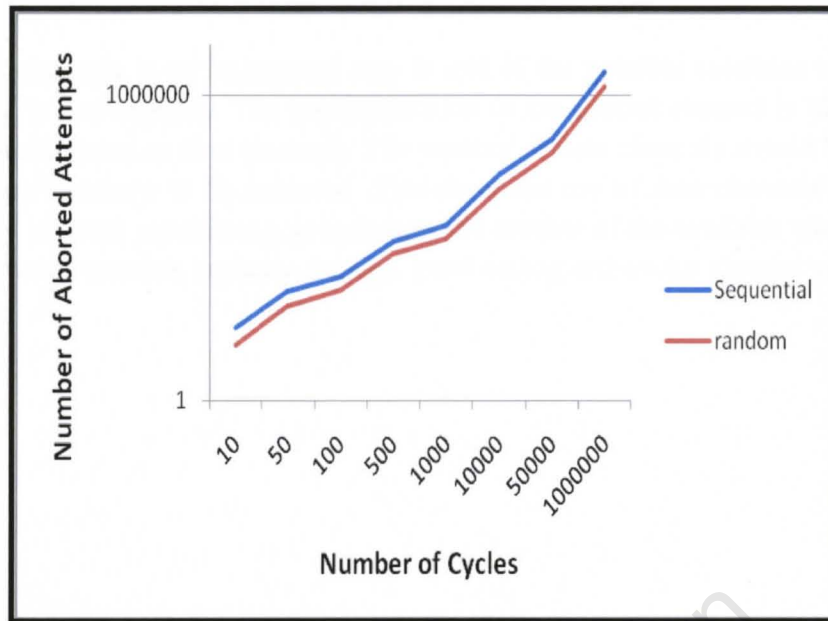


Figure 7. 4. The total number of aborted attempts

The average failure rate of the two schemes is shown in Fig 7.5. On average, the random algorithm had 1.5 unsuccessful attempts in each cycle (one cycle has six time slots) while the rate of the sequential algorithm was as high as 2.8 unsuccessful attempts in each cycle.

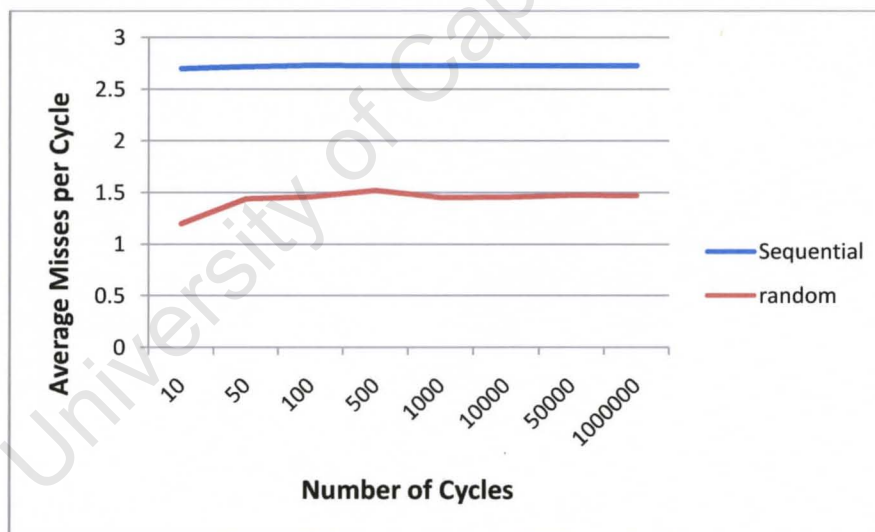


Figure 7. 5. The average failure rate per a cycle

7.4 Summary

This chapter has demonstrated that the capacity of multi-channel networks can be improved by assigning overlapping multiple channels in an orthogonal way at use. Widening the frequency guard bands to ensure that channels are orthogonal reduces the number of channels and degrades the capacity of multi-channel MAC protocols. The widening of frequency guard bands reduces the number of data channels to a level which degrades the performance of the

network. Using channels in an orthogonal way is one of the possible solutions to increase network scalability and capacity. The implementation of the control channel is ideal where there is a reasonable number data channels. The number of data channels should be at least five for better performance to be achieved. Therefore, the use of data channels in a non-overlapping way is worth considering. It maintains the number of the available channels and improves the overall network capacity through good orthogonal-aware channel assignment strategies.

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Chapter 8 Summary of Contributions and Future Work

8.0 Introduction

The CSA, a multi-channel MAC protocol to address a number of multi-channel interferences was proposed. The scheme implements a dedicated control channel and at least two data channels. It employs a single transceiver, which switches between the control and data channels. The scheme is designed to reduce the MSC, the signalling overhead cost, improve the utilization of multi-channels, and to improve the scalability of multi-channel MAC protocols. The project has demonstrated how the proposed CSA architecture reduces the effects of the HTP and the MRP. The scheme scales up well with the increase in the size of the network. The reduction of the amount of interference increases the scalability of the protocol. Next, we present the summary of the contributions of this thesis.

8.1 Summary of Contributions

The project characterized and modelled the MSC. The MSC was first identified in this project as being caused by the inability of the scheduling algorithms to schedule simultaneous transmissions to all the available data channels. It causes significant bandwidth wastage.

An algorithm which is based on the number of data channels was designed to compute the maximum bandwidth wastage owing to MSC. It is a *for loop* structured algorithm which calculates wasted bandwidth on each data channel. It then sums up individual data channel totals of wasted bandwidth to give the overall lost bandwidth.

The proposed CSA scheme reduces the MSC and limits it to the first cycle of data transmission. The MSC is not repetitive and does not recur in the proposed scheme. The utilization of the data channels has been improved by allowing data channels to be reserved before they become idle. The proactive reservation of data channels improves the utilization of the bandwidth of all the channels.

The existing multi-channel MAC protocols as shown in chapter three incur a high signalling cost, which degrades the capacity of the control channel. The proposed scheme has managed to reduce this cost by implementing the standard control packets. It further reduced it by improving the service rates of the control channel. The service rates were improved by reducing the idle durations of the control channel. The utilization of the control channel was also improved. Further strategies, which were employed to improve the service rates of the control channel, are as summarized in the following paragraphs.

The service rates of the control channel were also improved through the reconfiguration of the IFS. The EIFS was replaced with a shorter CIFS which was customised for multi-channel MAC protocols. The shorter IFS improves the service rates of the control channel.

The channel switching time was reconfigured and associated with the data channels. The nodes do not defer for the summation of the switching time and SIFS before transmitting data

frame on the data channel. Nodes switch to the data channels without deferring. The two switching times have been added to the data packet transmission.

The improvement of the service rates of the control channel has a performance benefit of improving both the capacity of the control channel and its capability to schedule more data transmissions. The improvement of the service rates of the control channel translates into the scalability of the network. The service rates increases the scalability of the network and improves its performance. It is more scalable than the IEEE 802.11 DCF MAC and the AMCP.

The project also proposed a network support infrastructure which consists of a network of mesh routers equipped with network intelligence. The network intelligence helps nodes to reserve data channels during the timeslots in which they are free. The network support systems provide the nodes with information regarding the availability of data channels and when the data channels can be reserved. The reservation of data channels is initiated before they become idle. The network support infrastructure ensures that nodes with incomplete network information initiate their next communication without having to defer for a very long duration. Joining nodes and returning nodes have inadequate knowledge of the network and such nodes benefit from the services of the network support infrastructure. Furthermore, the network support infrastructure increases the scalability of the network.

The support system also assists newly established networks to initiate communication. Nodes do not defer indefinitely waiting for overheard packets before initiating their communication. The network support system also increases the scalability of the network and the overall network capacity. The capacity of the network scales well with the increase in the size of the network. Though the network support infrastructure increases hardware costs, it comes with many benefits which are discussed above.

The channel saturation problem was investigated extensively. Contrary to what has been argued, the common control channel does not cause any system bottleneck. The investigation of this project proved data channels saturate ahead of the control channel. It further established that the number of data channels do not improve the performance of the network, though they increase the aggregated throughput of the system.

The analysis of the channel saturation problem also showed that the capacity of the control channel is degraded by the data channel when they are few. The control channel operates at an optimum level when the number of data channels is maintained at eight. When the data channels are increased beyond this point, the capacity of the control channel begins to degrade though it does not cause a system bottleneck.

The proposed CSA platform addresses other multi-channel interferences such as the MRP and the multi-channel HTP. The effects of these two interference challenges have been reduced in the proposed scheme. The HTP can be solved effectively by scheduling data transmission in cycles. The reservation of data channels is done sequentially to avoid the manifestation of HTPs on the data channels. An HTP can be missed on the control channel, which can later manifest on the data channel which then destroys data packets at reception. The missed

HTPs are handled by the CSA, which ensures that data channels are reserved in an orderly manner and sequentially to arrest the effects of hidden terminal challenge.

The implementation of the CSA platform has demonstrated that the effects of the missing receiver problem can be reduced by 25%, which improves the capacity of the control channel and the capacity of the overall network. However, this multi-channel interference challenge cannot be eliminated. Its effects are further reduced through the implementation of the network support infrastructure. The support system equips nodes with sufficient network information to combat the effects of the node deafness problem. Nodes initiate communication after they have acquired sufficient network information and when they are aware that the targeted node is available and is listening on the targeted channel.

The thesis also proposed a channel assignment algorithm which ensures that data channels are assigned in an orthogonal way.

8.2 Future Work

The thesis established that the multi-channel MAC protocols can be scaled up through the reduction of the signalling overhead cost, MSC, and improving the utilization of channels. The proposed scheme was investigated in an environment, which implemented static routing algorithms. The static routing algorithms do not clearly show the performance of the network. The performance of networks does not vary significantly when static routing agents are employed. This is evidenced by the end-to-end delay achieved by the LIFS scheme as compared to the results of the CIFS scheme in multi-channel MAC protocols.

For future work the proposed scheme may have to be implemented in a platform which implements dynamic routing algorithms. The scheme may also be implemented in large scale networks with more than thirty nodes. The current results have shown that the proposed scheme performs better in large networks.

The scheme may be investigated in different scenarios with different numbers of data channels. In all the investigations which, have been conducted in this project, only four data channels were implemented. Various combinations of channels may therefore be considered in the future. The number of data channels may be increased to six, eight and then to ten to investigate their effects on network performance.

The network support infrastructure nodes may be equipped with two radios, one for data transmission. The other radio may be dedicated to performing network support functions and operations such as the probing technique and the maintenance of the status tables.

The proposed CSA can be integrated with the VORCAAL as possible future enhancements. This can be done based on the maximum number of channels which can be supported by a single radio. A number of multi-channel schemes have assumed perfect orthogonality. This area may be investigated closely. The proposed VORCAAL may be further explored in the future.

Lastly, different network simulators such as the Network Simulator 3 (NS 3) may have to be considered. The protocol may also be enhanced and further optimized for better performance. A test bed implementation of the proposed protocol may also be considered in the future work.

8.3 Summary

The thesis investigated possible areas of scaling up and improving the performance of WMN. The use of multi-channels was identified as an approach which increases the scalability of WMN. However, the coordination, selection, scheduling and channel assignment challenges were identified as areas, which require further research. The common control channel approach was preferred for network connectivity. The project also identified a new multi-channel challenge we call the multi-channel scheduling cost, which has not been identified before.

The research has shown that the reduction of the signalling overhead cost and the MSC improves the performance of the network. The channel switching time was reconfigured and the channel idleness durations were reduced to improve network performance and the utilization of channels. The EIFS was reconfigured and changed to a shorter and appropriate inter-frame space, which improves network performance.

The new multi-channel challenge, the MSC has been limited to the first cycle in the proposed scheme. Its effects are not repetitive and recurring. As a result, the utilization of the control and data channels has improved.

The proposed CSA scheme may be implemented in real world or in test beds to investigate its performance under well known hardware constraints such as the broadcast and transmit-receive constraints. The HTP and ETP may also be investigated in these implementations.

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Appendix A: Delay.AWK

Delay.Awk

```
BEGIN {
    num_rcv = 0
    printf("# %10s %10s %5s %5s %15s %16s\n\n", \
        "flow", "flowType", "src", "dst", "time", "e2eDelay")
}
{
    # Trace line format: normal
    if ($2 != "-t") {
        event = $1
        time = $2
        if (event == "+" || event == "-") node_id = $3
        if (event == "r" || event == "d") node_id = $3
        flow_id = $6
        pkt_id = $18
        pkt_size = $8
        flow_t = $7
        #level = "AGT"
        level = "MAC"
    }
    # Trace line format: new
    if ($2 == "-t") {
        event = $1
        time = $3
        node_id = $5
        flow_id = $39
        pkt_id = $41
        pkt_size = $37
        flow_t = $45
        level = $19
    }
    # Store packets send time
    if (level == "MAC" && flow_t == "tcp" && node_id == src &&
        sendTime[pkt_id] == 0 && (event == "+" || event == "s") && pkt_size >= pkt) {
        sendTime[pkt_id] = time
    }
    # Store packets arrival time
    if (level == "MAC" && flow_t == "tcp" && node_id == dst &&
        event == "r" && pkt_size >= pkt) {
```

```

        rcvTime[pkt_id] = time
        num_rcv ++
        arrival[pkt_id] = pkt_size
    }
}
END {
    # Compute average end-to-end delay
    tmp_rcv = e2eDelay = sum = 0
    prev_time = delay = processed = currTime = 0
    prev_delay = -1
    for (i=0; processed<num_rcv; i++) {
        if(rcvTime[i] != 0 && arrival[i] != 0) {
            tmp_rcv++
            if(prev_time != 0) {
                delay = rcvTime[i] - prev_time
                sum+=arrival[i]
                e2eDelay += rcvTime[i] - sendTime[i]
                if(delay < 0) delay = 0
                # This 'if' is introduce to obtain clearer
                # plots from the output of this script
                if(delay >= tic*10) {
                    printf(" %10g %10s %5d %5d %15g %18g\n", \
                        flow,flow_t,src,dst,(prev_time+1.0),0)
                    printf(" %10g %10s %5d %5d %15g %18g\n", \
                        flow,flow_t,src,dst,(rcvTime[i]-1.0),0)
                }
                currTime += delay
                if (currTime >= tic) {
                    printf(" %10g %10s %5d %5d %15g %16g\n", \
                        flow,flow_t,src,dst,
sum/tmp_rcv,e2eDelay/tmp_rcv)
                    e2eDelay = 0
                    sum=0
                    currTime = 0
                    tmp_rcv = 0
                }
            }
            prev_time = rcvTime[i]
            processed++
        }
    }
}
END {
    printf(" %10g %10s %5d %5d %15g %18g\n", \

```

```

        flow,flow_t,src,dst,(prev_time+1.0),0)
printf(" %10g %10s %5d %5d %15g %18g\n", \
        flow,flow_t,src,dst,(recvTime[i]-1.0),0)
printf("\n\n")
}
function abs(value) {
    if (value < 0) value = 0-value
    return value
}

```

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Appendix B: VORCAAL Code

VORCAAL

```
for(i = 0; i < Number_Of_Cycles; i++)
{
    for(j = 0; j < Slots; j++)
    {
        if (Current_channel < Last_channel)
        {
            Selection_Success += 1;
            Current_channel = Current_channel + 2;
        }
        else
        {
            Selection_Success += 1;
            Current_channel = First_channel;
        }
    }
}
```

Random

```
for(i = 0; i < Number_Of_Cycles; i++)
{
    for(j = 0; j < Slots; j++)
    {
        if ((Current_channel - Selected_channel) > 1)
        {
            Selection_Success += 1;
            Selected_channel = Current_channel;
        }
        Current_channel = rand() % 11 + 3;
        if (Current_channel < Selected_channel)
        {
            swap = Current_channel;
            Current_channel = Selected_channel;
            Selected_channel = swap;
        }
    }
}
```

```

    }
}

```

Sequential

```

for(i = 0; i < Number_Of_Cycles; i++)
{
    for(j = 0; j < Slots; j++)
    {
        if ((Current_channel - Selected_channel) > 1)
        {
            Selection_Success += 1;
            Selected_channel = Current_channel;
        }
        if (Current_channel < Last_channel)
            Current_channel = Current_channel + 1;
        else
        {
            Current_channel = First_channel;
            Selected_channel = Control_channel;
        }
    }
}

```